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PROJECT SQUID

QUARTERLY PROGRESS REPORT

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QUARTERLY PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH

ON LIQUID ROCKET AND PULSE JET PROPULSION

FOR THE

BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

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CONTRACT N6ORI-11, TASK ORDER II

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INTRODUCTION

Technical

During the third quarter of 1947, steady progress on all phases of Project SQUID at New York University has been made. Because of the fundamental nature and scope of most of the problems undertaken, it has not for the most part been deemed advisable to write bona fide technical reports on the investigations pursued thus far. These investigations have yielded many results which have been duly included in the regular progress reports, but, scientifically speaking, most conclusions which might be drawn must still be classed as tentative and subject to further test and study.

The combustion studies of Phase 1 continued with (1) the application of more accurate techniques on the experimental side and (2) a further check of the theory of flame propagation in tubes. The electronic apparatus for the experimental study of specific heats at high rates of change of temperature has been rebuilt, and a theoretical investigation of thermocouple measurements in rocket walls has been carried out for Phase 2. Several analogue devices for studying the boundary conditions at the ends of pulse jet tubes and the internal gas flow in pulse jets have been developed as part of Phase 3, while construction work is proceeding (1) on modifying the full scale pulse jet for better control and (2) on a new test site. The continued improvement of pressure measuring instruments, with the application of the sodium D-line reversal method to a study of the effect of sodium concentration on temperature measurements has marked progress on Phase 4. As a result of the application of schlieren techniques to the observation of flow at the exhaust end of miniature pulse jets, the theoretical study of drag and flow of Phase 5 shows promise of considerable advancement in the near future.

Plant

The University is constructing a new building, floor area 20×96 feet, adjacent to and paralleling the thermomechanics laboratory for the use of Project SQUID. It is hoped that the Project group will be able to move in before November 15, consolidating the group in two adjacent buildings.

As shown in Figure 1, the northern half of the building is to be used for a machine shop, work

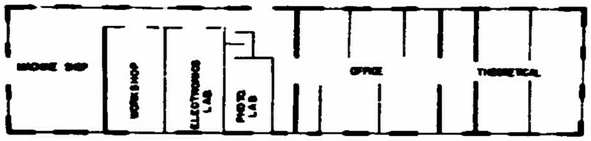


Figure 1. Layout of new building for Project SQUID, N.Y.U. at University Heights.

room, electronics laboratory, and photographic dark room; the southern half, for general office space for project members, and a quiet section for theoretical work.

During August and September, negotiations were carried on for a new test site, 100×100 feet including an access road and police protection, at Westchester County Airport at Rye Lake, New York. As soon as the lease is signed, work will be commenced by Parks Nurseries of White Plains, New York, to grade the area and install a cinder and sand hard top and a fire break. The surveying of the area has been completed, including mapping and leveling. The site should be ready for use about a week after the lease is closed.

At the site we plan to have the following equipment in use, as shown in Figure 2.

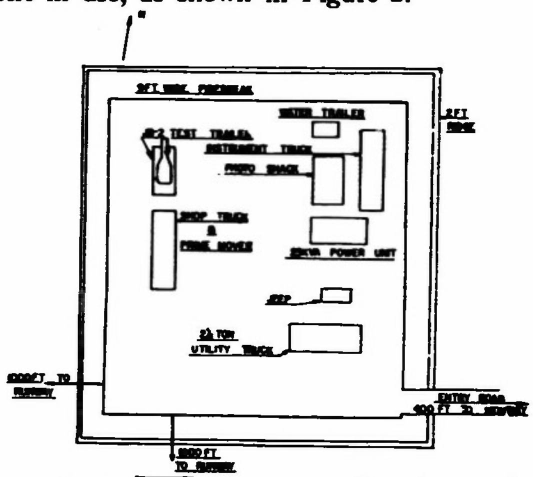


Figure 2. Jet engine test site, Westchester County Airport.

a. An SCR-268 trailer with the full scale JB-2 and thrust stand mounted as a self-contained unit. This unit will operate on 110 volts a.c. and needs 200 p.s.i. air supply and fuel for the engine.

b. A four-wheel flat-bed trailer with an eleven by nine foot photo and control shack to be built on it. This shack, which is now on the drawing board, will have a six by four foot plate glass window through which the high speed cameras will operate. It will also contain the bomb control panel, have running water and a chemical toilet, and will be heated by electric unit heaters to permit winter operation.

c. A 25 k.v.a. 110 volt a.c. motor generator trailer which will be used as a general power supply for all operations.

d. An electronics trailer for general instrumentation purposes.

e. A six-ton White military 6 × 6 truck which will be used as a prime mover for the JB-2 trailer and will contain our maintenance shop for the field maintenance of all the equipment. Other prime movers, including a four-ton Autocar tractor on loan from the Navy, and a Brockway tractor, are available for the other units, thus making the whole set up mobile.

f. The Research Division Willys Jeep Station-Wagon for personnel transportation and utility cargo use, and a 2½-ton GMC military 6 × 6 with a van body for heavy utility transport.

All the above mobile units are now on hand and the necessary construction work and modifications are being carried out.

PHASE NO. 1

In connection with pulsating jet engines: to undertake theoretical and experimental investigations of (1) flame motions with controlled initial turbulence, (2) stationary flames with controlled turbulence, (3) suitable theoretical models based on the above observations, and (4) statistical mechanics of non-uniform gases.

Summary

Experimental work on flame propagation in tubes continued with the application of more accurate techniques. Data from these experimental studies were applied toward development of the theory of flame propagation in turbulent media.

A schlieren technique was used for recording phenomena at the lip of the flame tube. This technique is now being extended to the tube of square cross section and to other positions in the tube.

Some pressure measurements have been made at the lip of the tube with a magnetostriction gauge and a condenser-type gauge.

Burner flame experiments were temporarily slowed because of delay in obtaining equipment. They are expected to begin again shortly.

Shock wave ignition experiments have been halted temporarily because of the necessarily rapidly increasing complexity of the apparatus, pending ideas on a modified method of attack on this difficult problem.

Experimental

MOVING FLAME EXPERIMENTS. *Velocity Measurements.* Measurements of the velocity of flames in a propane-air mixture in tubes containing grids have been considerably extended and made more accurate through the use of techniques employing a streak camera, with the timing accomplished by means of light from a Strobotac reflected on to the film. These velocities have been found to be reproducible to ±1%. The velocity of flames in tubes not containing grids are not reproducible in detail.

Figures 3 and 4 show photographs, taken with a streak camera, of flames in tubes with and without grids, respectively. The vertical axis represents distance which can be measured from the igniter at the closed end of the tube, the ignition occurring at the bottom left hand corner in the figures. The horizontal axis represents time. The timing marks are seen at the top of the photographs. For Figure 3 the time between two marks is 0.00417 seconds and for Figure 4, 0.0167 seconds. The distance from the grid to the open

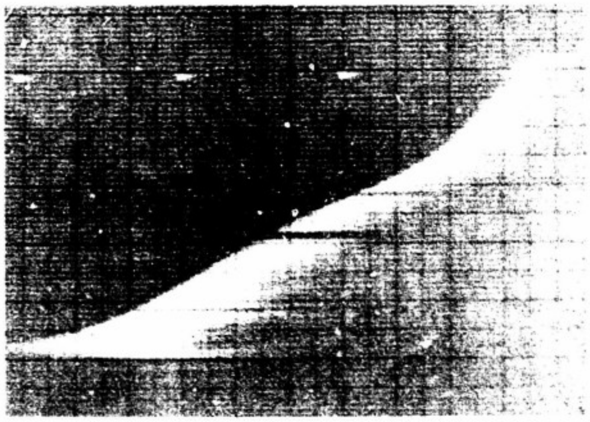


Figure 3. Flame in tube with grid. Average flame velocity is about 600 ft./sec. The photograph was made with a streak camera.

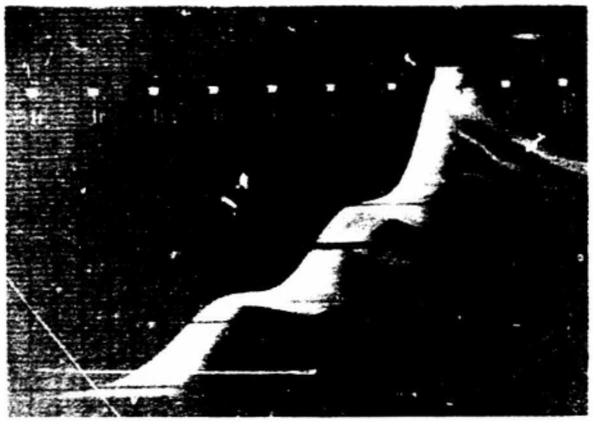


Figure 4. Flame in tube without grid. Average flame velocity is about 70 ft./sec. Compare with Figure 3.

end of the tube, located at the top in Figure 3, is 7.24 feet. The grid was placed 0.42 feet from the closed end of the tube. The distance from the closed to the open end of the tube in Figure 4 is 7.66 feet. A rectangular coordinate system has been superimposed on the photographs to facilitate interpretation.

An extensive study of the behavior of flames in tubes containing grids has been made. The following parameters have been varied: length of tube, attitude of tube (horizontal or vertical), cross-sectional configuration of tube, position of grid, and type of grid. Now under study are the effects of a variation of the mixture ratio and the kind of combustible gas.

The following experimental conclusions have been reached.

1. When a waffle-like grid is placed in the tube, flame front velocities and position-time curves are reproducible to within one per cent.
2. The positions of the maxima and minima of the time-position curves are a function of the length of the tube. Velocities are likewise a function of the tube length.
3. The orientation of the tube with grid (horizontal or vertical) and the cross-sectional configuration of the tube (square or circular) have apparently no influence on the shape of the time-position curve of the flame front.
4. Burning in a tube without a grid is not reproducible in so far as velocity and time-position curves are concerned. Average flame velocities in tubes without grids are slower by a factor of ten than in a tube with grids.
5. While the apparent duration of burning of a given layer of gas cannot be stated accurately at this time, in the tube with a grid the duration seems to be about 8 milliseconds.

Experimental data has been obtained but is not yet interpreted for the variation of flame front propagation velocity in tubes for the following conditions:

1. Variation of position of grid in the tube.
2. Variation of design of grid. Among the grids used were a fly screen grid, grids of the customary waffle type with varying ratios of blocking to open space, and grids without trailing edges.
3. Variation of mixture ratio between minimum and maximum limits of inflammability.
4. Variation of combustible gas, i.e. butane instead of propane.

Schlieren Experiments. Schlieren movies at high speed have been made of the motion of gas at the lip of a cylindrical tube during combustion in the tube. The two cases of combustion in a tube with a grid and without a grid were considered. In an extension of this study, photographs will be made of the behavior of the gas immediately below the grid and at points between the grid and the lip. The tube with square cross section will be employed in these experiments.

Pressure Measurements. Attempts at measuring the transient pressures close to the open end of the six foot long tube with a square cross section using a magnetostriction pick-up element were largely unsuccessful because of the lack of sensitivity of this element. Preliminary conclusions based on the results of these experiments seemed to indicate that at no time before, during, or after combustion in the tube did the pressure exceed 3 or 4 p.s.i. However, when the condenser pickup was substituted, a definite pressure spike was observed, as in Figure 5. Detailed study indicates a peak pressure of 6.0 p.s.i. with a "duration" of 0.5 milliseconds, and a negative pressure phase just preceding the peak of about —2.0 p.s.i.

BLOWER UNIT. The blower unit is completed, except for the exhaust system and inlet and outlet connections to the cooling system. The date of the initial running tests depends entirely on the supply of these parts, which we hope to obtain in a short time.

Theoretical

WAVE AND FLAME PROPAGATION IN TUBES. Extending the theoretical calculations on wave

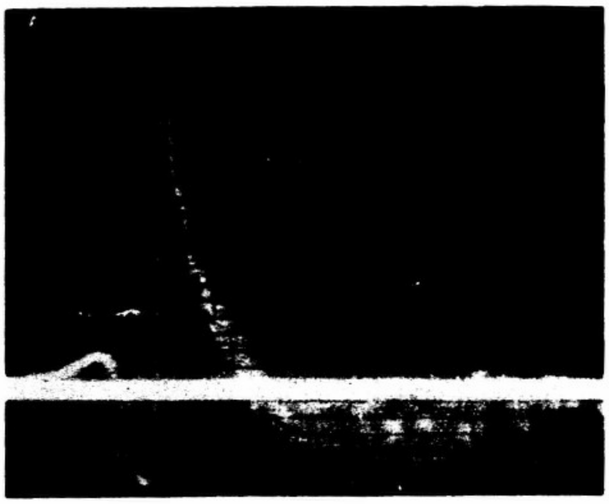


Figure 5. A recording of the transient pressure pulse at the end of a flame tube, obtained with the FM condenser gauge. Peak pressure 6.0 p.s.i. Minimum —2 p.s.i. Time increases to the right. Time of pressure pulse from rising branch on x-axis to return to x-axis is ½ millisecond.

and flame propagation in tubes described in the *Quarterly Report* dated 1 July 1947, the non-linear one-dimensionalized aero-thermodynamical equations were integrated numerically by using two families of characteristics ahead of the flame and by using three in the flame region. The results were found to be remarkably well approximated in typical cases by explicit analytical solutions of linearized aero-thermodynamical equations expressed in terms of Lagrange coordinates. (This good approximation feature is regarded as important in connection with the theory of pulse jets.) The calculations involve three combustion parameters:

(1) the 'intrinsic Langrangian flame speed',
(2) the 'effective rate of release of energy of combustion per unit mass',
(3) the 'effective duration of burning of a thin layer of turbulent gas'.

Typical experimental curves of flame front position versus time were found to be quite well represented by the idealized theory. In this theory the pressure at the open end of the flame tube is treated as constant. Experimental results based on condenser-type pressure pickups support this boundary condition except for relatively brief pressure pulses presumably associated with shock waves arising during the ignition process. Technical Reports on the experimental and the theoretical investigation on flame tubes are being prepared.

Future Plans

Schlieren movies of the motion of gases in the flame tube will be made. A special burner has been designed and is being constructed, which, it is hoped, will furnish clues as to the nature of turbulent burning. Experiments are to be undertaken to determine if strong sound waves affect the rate of burning in tubes.

Theoretical calculations based on variable parameters of combustion will be made and compared with measurements of pressures, temperatures and velocities in flame tubes and in pulse jets. Theoretical models for turbulent combustion are expected to be suggested by the proposed schlieren movies.

PHASE NO. 2

In connection with liquid rockets and pulsating jet engines: to study (1) measurements of temperature dependence of conductivity and heat capacity of steels and other materials, (2) adiabatic calorimetry and metallography, (3) characteristics of heat transfer between hot flowing gases and walls, using measurements of gas velocity and temperature by radiation and thermocouple devices, (4) calculations of temperature changes in jet and rocket walls.

Summary

Work on the measurement of specific heats of steel at high rates of change of temperature has proceeded with the rebuilding of the apparatus.

Theoretical calculations have been made of the error introduced in measuring the transient temperature in a rocket wall by using even a tiny conventional type thermocouple.

Experimental

Specific Heat of Steel at High Rates of Change of Temperature. Since the first preliminary results were obtained, the apparatus has been rebuilt and improved. The electronic amplifiers and an electronic switch are now under test.

The apparatus is designed to operate as follows. The specimen in the form of a cylindrical rod is placed in an evacuated cylindrical glass chamber whose inside surface is silvered. The rod will be heated by storage batteries at the rate of 1000° K/sec. A very small platinum platinum-rhodium thermocouple is welded to the center of the specimen rod. The output is amplified by a d-c amplifier put on an oscilloscope with time pips superimposed on the curve. Separate leads across the specimen will pick up the voltage across it while the voltage across a known resistance in series with the specimen will give a measure of the current. These two quantities are applied to the input of an electronic switch whose output is a square wave of 200 cycles per second. The level of the top and the bottom of the square waves varies with variation of the two input quantities. The breaks in each curve provide a time base.

THERMAL CONDUCTIVITY AT HIGH RATES OF HEATING. If the present method of measuring specific heat proves to be experimentally feasible, it should be possible to measure the thermal conductivity with slight elaboration of the apparatus. An electric heating coil would be placed around one end of the rod under test and two thermocouples would then measure the variation of temperature with distance along the rod during a rapid heating by the method already described.

WEDGE THERMOCOUPLE FOR MEASUREMENT OF TEMPERATURE IN ROCKET WALLS. Theoretical studies by Dr. J. K. L. MacDonald indicated an optimum shape for a quartz wedge thermocouple which should be sensibly free of perturbations.

The quartz wedges have been delivered and there remains the problem of sputtering the two metals adjacently along a knife edge .010 inch wide. This will be attempted in a few weeks.

The specimens will be sent to Dr. C. T. Elvey for test at N.O.T.S., Inyokern, California.

Theoretical

TEMPERATURE PERTURBATIONS DUE TO THERMOCOUPLE STRUCTURES. A numerical integration of the heat conduction equation for a non-steady flow of heat in a composite solid simulating a thermocouple wire in a hole in a rocket wall, has been completed and confirms the results of an earlier computation. Perturbations in the temperature readings can be as great as 30% of the early temperature rise, even for holes .007″ in diameter with wires .003″ in diameter. A Technical Report on the subject is being prepared.

Future Plans

Specific heat measurements are to go ahead, and when completed the apparatus will be modified slightly to proceed with thermal conductivity measurements. A "perturbation-free" thermocouple is to be completed and tested.

PHASE NO. 3

In connection with liquid rockets and pulsating jet engines: (1) to observe flame and particle motion, pressures, temperatures, densities and effects of turbulence in pulsating and rocket jet devices; (2) to study water stream analogues for gas motion in pulsating jets and rockets in order to determine characteristics of simple theoretical models, and (3) to use the above for theoretical treatments of the internal ballistics of jet devices on the basis of justified simple models.

Summary

The full scale pulse jet tests have been temporarily halted because of the termination of the contract for the test site at Dover, New Jersey, and because of the necessity of modifying the JB-2 for better control in starting and stopping. These modifications, together with a mobile thrust stand trailer, are almost complete.

Several water and smoke analogue devices for the study of compressible and non-compressible non-steady flow inside pipes and from pipe ends have been constructed. Work is proceeding on a mechanical analogue for aero-thermodynamics.

Experimental

FULL SCALE PULSE JET TESTS. Several more night tests of the PJ-31 engine at Reaction Motors, Inc., in Dover, New Jersey, were made in July to determine a suitable design for pyrex windows to cover the holes drilled along the pulse jet tube. A design which shows promise of withstanding the heat and pressure was evolved and will be tested when operations are renewed. Figure 6 shows a sequence of high-speed photographs of the flames at the exhaust end of the PJ-31 engine, covering a single cycle (1/40 second) of its operations. One effect of the absence of windows cov-

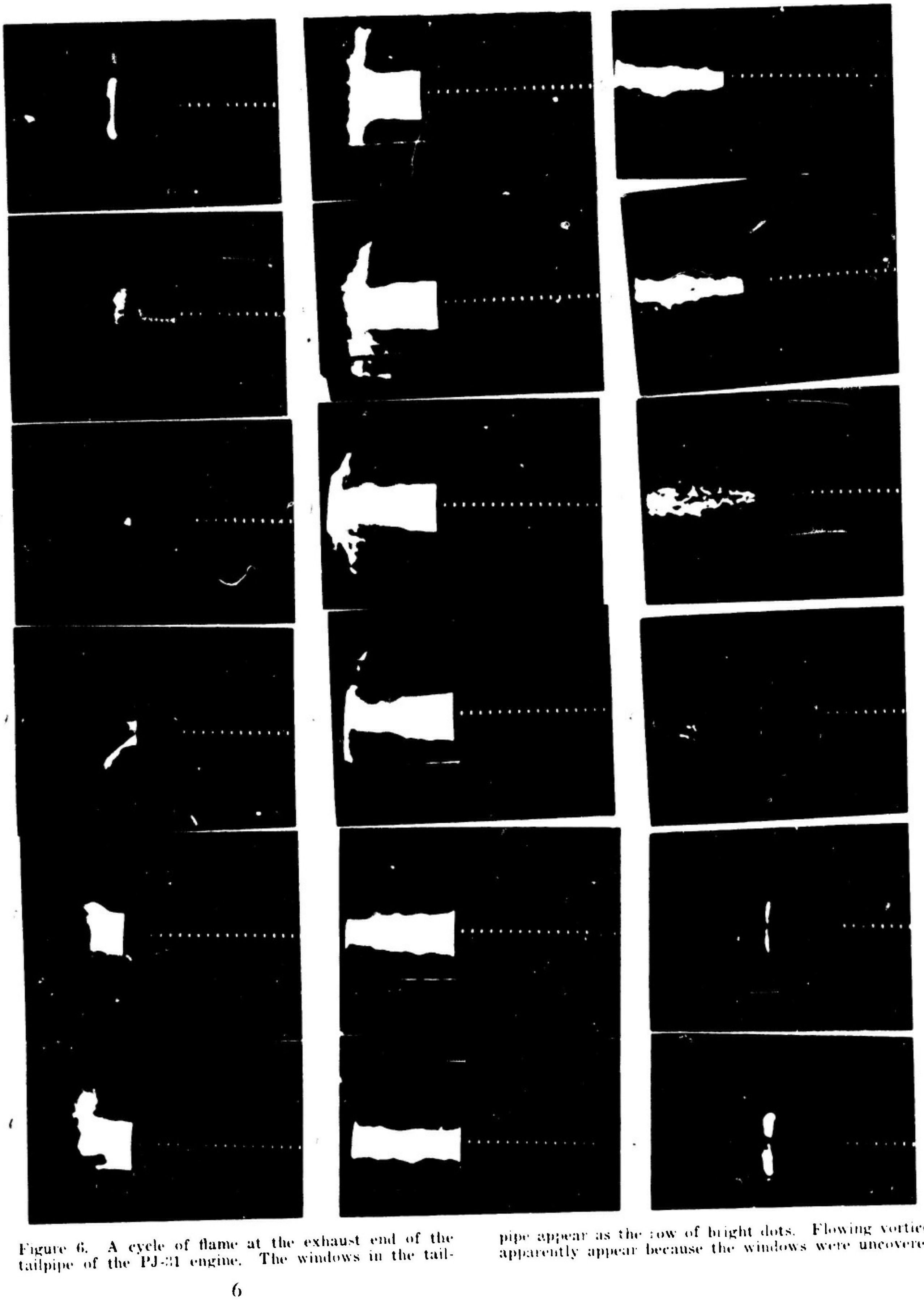


Figure 6. A cycle of flame at the exhaust end of the tailpipe of the PJ-31 engine. The windows in the tailpipe appear as the row of bright dots. Flowing vortices apparently appear because the windows were uncovered.

ering the holes drilled along the sides seems to be the flaming vortex which appears at the beginning and end of the cycle shown. Another effect is the more or less continuous burning within the tailpipe, shown by the luminous spots in the photograph. On 31 July 1947, the contract with Reaction Motors, Inc., was terminated and on 1 August the JB-2 and its supporting equipment was moved to the University Heights Campus.

MODIFICATIONS OF THE JB-2. During the rest of this quarter certain modifications of the full-scale pulse jet engine and its control apparatus were proposed and are now almost completed.

This new system, first suggested to us by Lieut. J. M. Simpson, U.S.N., of Point Mugu, California, is arranged so that the control system can be operated from a remote point through a switch bank and solenoid valves. The starting air and fuel meter air have been separated to permit internal purging and pre-loading of air in the engine tube. Under the new arrangement all the solenoid valves and controls are mounted inside the bomb fuselage. The only outside connections are the 200 p.s.i. air supply, the 24 volt power supply, and the cable of five lines to the control board. This new setup will permit safety of operation and better control, and during bad weather it will permit the operators to be in a shelter while operating the engine. The changed air-fuel system is expected to permit a higher percentage of good starts and less danger of fire from delayed purging of unburned fuel.

THRUST STAND FOR FULL-SCALE TESTS. The design for the full-scale thrust stand was completed early in August and bids were taken. The complete bids were too high so the job was broken into segments and new bids were let. The machining work is being done by L. C. Eichner Instruments of Bloomfield, New Jersey, and is about half completed. The structural steel parts are being fabricated by the Peerless Iron Works of the Bronx, and we intend to do the assembly work ourselves. It is hoped to have the thrust stand completed, the modified JB-2 mounted on it, and both mounted on the SCR-268 trailer, as shown schematically in Figure 7, some time in November.

WATER AND SMOKE ANALOGUE DEVICES FOR STUDYING UNSTEADY COMPRESSIBLE FLOW. Several glass-walled pistons and cylinders have been constructed for observing with a smoke tracer the influx and efflux of air at the end of a cylinder as the piston is moved. One piston and cylinder is circular in cross-section, and interesting smoke rings somewhat analogous to the vortex rings from the tailpipe of a pulse jet have been observed with it. Another is rectangular in cross section and is enclosed between two large parallel glass plates so that the flow is two-dimensional. The flow pattern from this arrangement, which of course corresponds to incompressible fluid flow, will be compared with nonsteady water flow issuing from a shallow vertical-walled channel into a large shallow tank. This flow corresponds to compressible flow in two dimensions with gamma equal to 2, the analogue of density being proportional to the depth of the water and the analogue of pressure being a quantity proportional to the square of the water depth.

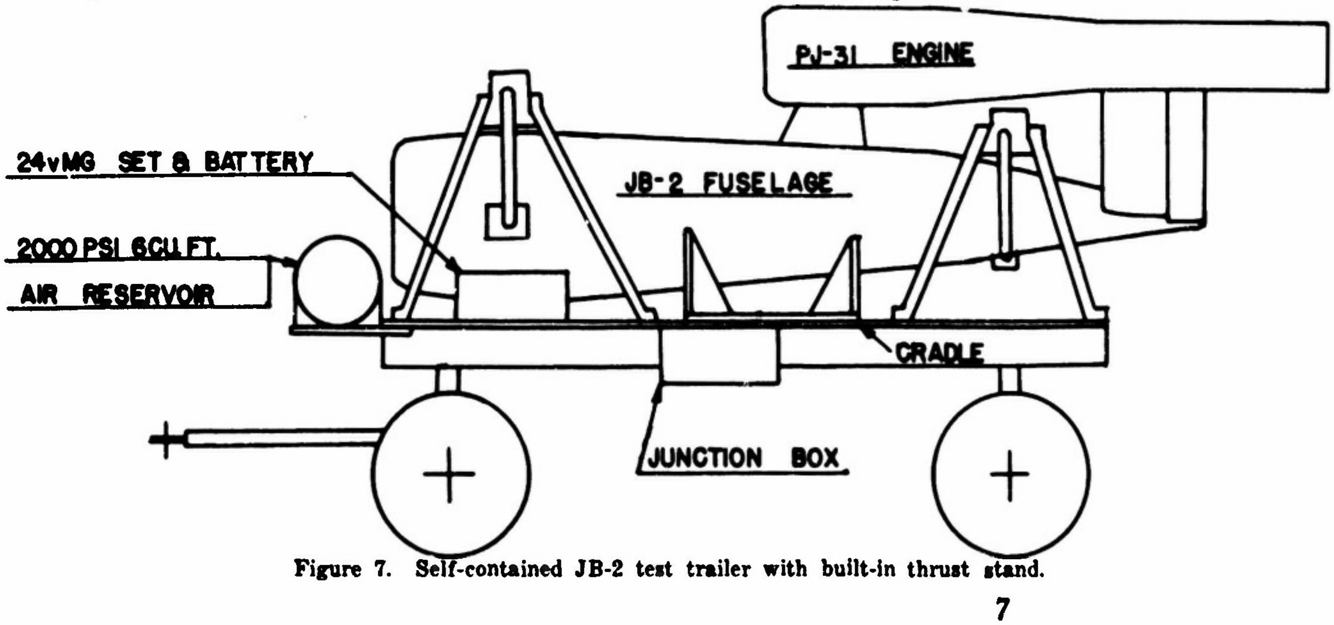


Figure 7. Self-contained JB-2 test trailer with built-in thrust stand.

Theoretical

MECHANICAL ANALOGUE MODEL FOR AERO-THERMODYNAMICS. Formulas have been developed showing the forms of controlled variable spring forces (or magnetic forces) required between adjacent masses in a model in order to simulate one-dimensionalized propagation of waves and flames in tubes of variable cross section. Practical methods for controlling these forces are being investigated, and the construction of a working model is planned. Such a model would provide numerical results in a small fraction of the time required for numerical integrations of the non-linear aero-thermodynamic equations referred to in Phase 1.

WATER ANALOGUE FOR COMPRESSIBLE ONE-DIMENSIONAL CHANNEL FLOW. A study of the flow of water in an open channel having a cross section other than rectangular leads to a water analogy to compressible air flow in one dimension, with gamma, the ratio of specific heats, different from the value 2 occurring in the usual water analogies. Under the assumption that the flow velocity along the channel is uniform over any cross section, and that accelerations at right angles to the channel axis are negligible, it turns out that a simple V-section channel will simulate a compressible flow with gamma equal to 1.5. In this analogy, the analogue of pressure is a quantity proportional to the cube of the depth of water, whereas the analogue of density is a quantity proportional to the square of the water depth. Two V-shaped channels with different apex angles have been constructed to study this analogue.

Future Plans

It is planned to further modify the fuel system of the JB-2 pulse jet to bypass the fuel meter and permit throttling of the engine. This change will not be attempted until after the present modifications have been fully tested. Upon completion of these modifications, a complete technical manual on the new setup and operation of the PJ-31 engine will be published.

A mechanical analogue for aero-thermodynamics is to be constructed, and attempts will be made to introduce an analogue of combustion into water analogies. Further studies of small-scale pulse jets, including particle velocity measurements as well as flame velocities, are to be made.

PHASE NO. 4

In connection with liquid rockets and pulsating jet engines: to develop instruments for recording transient thrust and pressures, temperatures, and densities of h t oscillating gases, and gas velocities.

Summary

The condenser-type pressure gauge is showing most promise for use in transient pressure measurements. Work is proceeding on dynamic calibration methods.

It has been determined that by aspirating salt solution of different concentrations into a flame, very little, if any, effect is observed on the temperature measured by the sodium D-line method.

Work is proceeding on fluid velocity measurements by use of thermistors.

Pressure Gauges

CONDENSER-TYPE GAUGES. The internal design of the condenser gauge has been improved as in Figure 8. The diaphragm is integral with the case. The inside of the diaphragm and the electrode are highly polished. It is possible to hold the diaphragm separation to less than .001″.

The circuit used with this gauge is shown in Figure 9. In connection with this, it should be noted that if a Dumont 241 Oscilloscope is used, the receiver amplifier may be replaced by the amplifier of the oscilloscope.

The sensitivity of the gauge at a gain of 1/20 is two pounds pressure per inch of deflection on the scope. A check for microphonics was made by closing off the pressure diaphragm with a heavy steel diaphragm and inserting this assembly at the open end of the flame tube. The observed total amplitude was then 0.3″. The electrical frequency response was better than the natural frequency response of the diaphragm. The latter is computed to be 16.5 kilocycles per second for a diaphragm thickness of .020″ and a diameter of .500″.

Calibration so far has been by the bursting diaphragm method. The response is linear to 45 p.s.i. within the probable error of reading the bursting

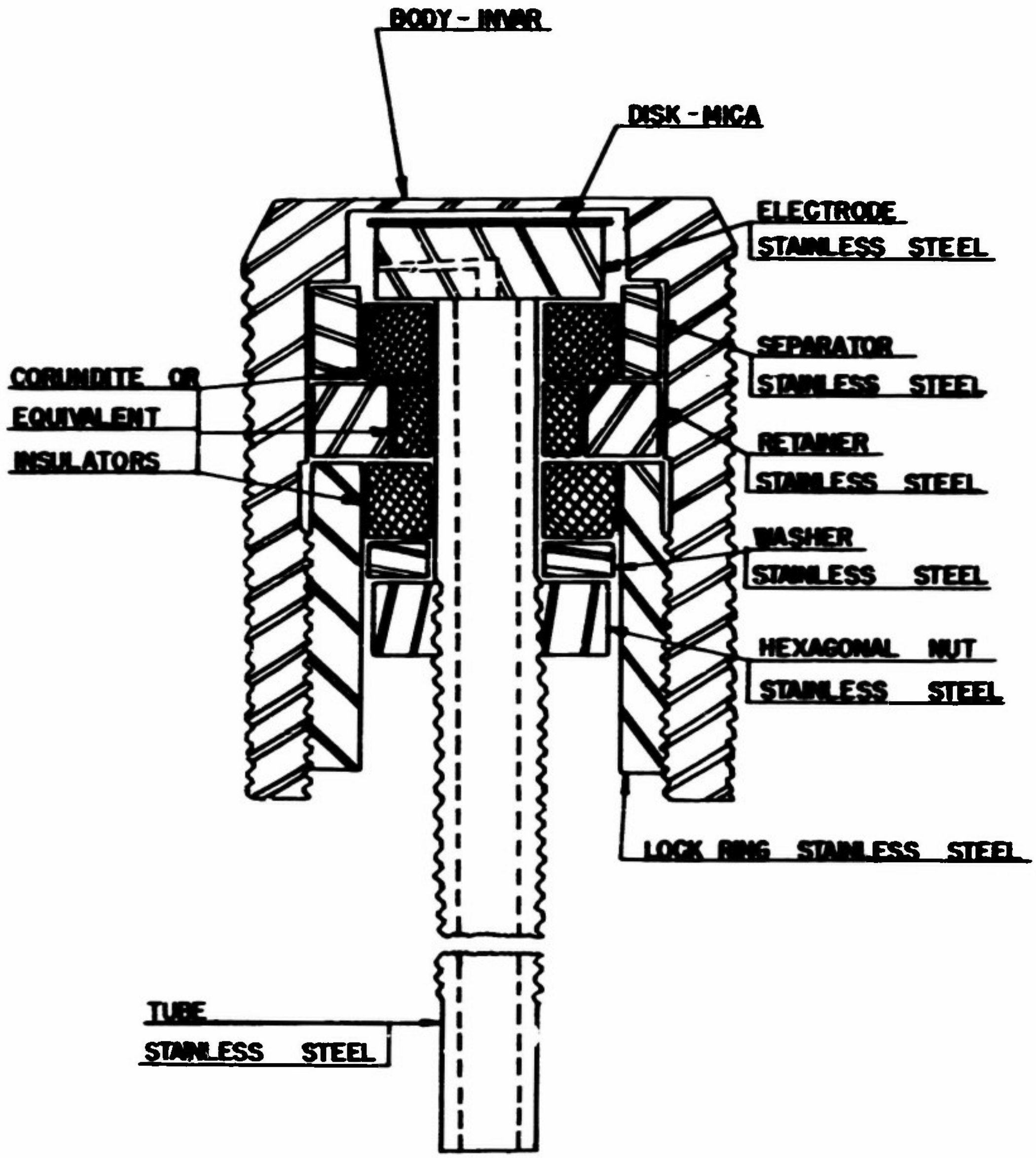


Figure 8. Interior design of the condenser-type pressure gauge.

pressure. The mechanical pressure calibrator with rubber diaphragm is being re-assembled.

Preliminary tests were made using an air jet for calibration at 100 p.s.i., interrupted 600 times a second with a rotary chapper. The condenser gauge gave a definite wave form. It is planned to investigate a more refined device to give higher frequency and better control of the air flow.

MAGNETOSTRICTION GAUGE. The use of an amplifier for the integrating circuit is a distinct improvement, but there are still some microphonics in this system. Furthermore, this gauge is not sensitive enough to pressures under 10 p.s.i.

Cooling Device

The condenser gauge is cooled by a fire tube type cooling chamber with water at 78 pounds per square inch pressure. The inside surface of a stainless steel diaphragm .015" thick stabilizes at

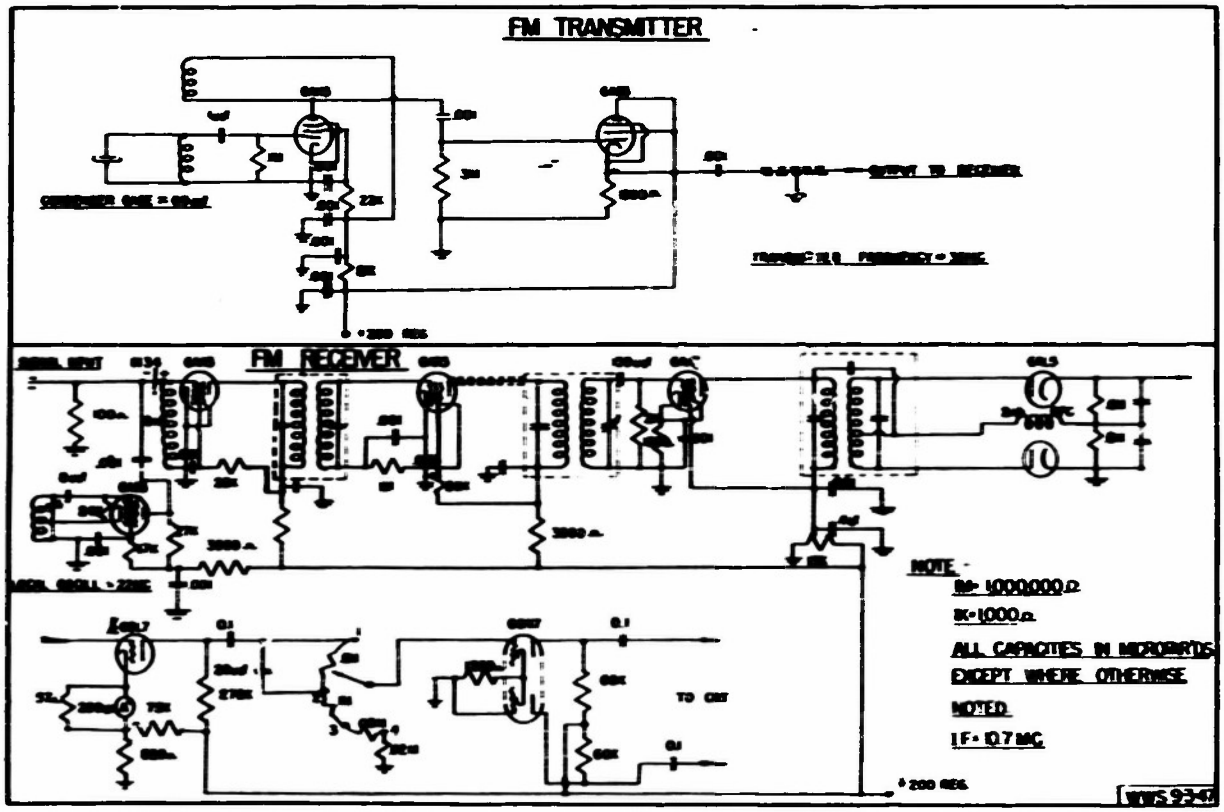


Figure 9. Wiring diagram for the FM condenser-type pressure gauge.

98° F. after 13 seconds operation of a Dynajet. This was measured with a thermocouple. This chamber will be further tested on the JB-2.

Effect of Sodium Concentration on Temperature

Normality of Solution	Temperature °K	Deviation from Average
.1	2067	—19
.2	2063	—23
.3	2095	+ 9
.4	2086	0
.5	2091	+ 5
.6	2095	+ 9
.7	2077	— 9
.8	2095	+ 9
.9	2105	+19
1.0	2086	0
	Av. 2086	
1.0	2095	+ 2
2.0	2086	— 7
3.0	2105	+12
4.0	2091	— 2
5.0	2091	— 2
	Av. 2093	

Temperature Measuring Devices

Sodium D-Line Reversal Method. A careful study has been made of the effect of sodium concentration on the determination of temperature. Varying concentrations of sodium chloride were dissolved in water and then aspirated at 40 p.s.i. air pressure into a special burner using city gas. The observations of the reversal point were made by eye, using a calibrated lamp. The table in the opposite column gives the results of this study.

It should be noted that the temperature measurements are independent of the concentration, but that the error of measurement increases considerably at the lower concentrations.

Some work is also being done on the effect of light scattering in the flame.

Work is continuing on the development of the d-c amplifier. This appears to be more rewarding than attempts to increase the frequency of the inverter which had previously been used to modulate the d-c signal.

Through the courtesy of Dr. P. S. Myer of the University of Wisconsin, a Dynajet with a quartz window, supplied by us, will be tested using a two color photometer (cf. *ASME Transactions*, January 1946, Vol. 68, p. 17).

Other Methods. The two-line color method and attempts to measure the temperature from the continuous background both depend essentially on a knowledge of the absorption coefficients of gasoline flames at varying pressures. As these coefficients are not known, it is planned to measure them in the JB-2 as a prelude to further work using these methods.

Fluid Velocity Measurement by Thermistors

To determine the frequency response of the thermistor, a bridge and audio-signals are used, the procedures being similar to those for hot wire anemometers (reference, N.A.C.A., TN 1331).

Work is being done on the design of streamlined flow devices for proper immersion of the thermistor in the liquid. The thermistors have been supplied to us through the courtesy of the Western Electric Company and are of the open flake type.

Future Plans

An attempt will be made to determine the optimum temperature difference of thermistor and liquid. Considerations are being given to the design of improved compensator circuits.

We are investigating the possibility of solving the thermistor-anemometer equation by the methods suggested by Martinelli and Randall (cf. *ASME Transactions*, January 1946, Vol. 68, p. 75).

PHASE NO. 5

In connection with liquid rockets and pulsating jet engines: to study drag characteristics of pulsating jet and other devices under conditions of nonsteady or of supersonic flow, using firing range photography, wind tunnel measurements, and theoretical investigation.

Summary

Schlieren motion pictures of the flow at the exhaust end of a pulse jet in operation have been made and lead to a semi-quantitative description of the flow and jet action.

Experimental

Schlieren Observations on Non-Steady Flow at the Exhaust End of Pulse Jets. In July and August, high speed schlieren motion pictures were made of the exhaust end of a Dynajet in action. The optical arrangement is shown in Figure 10. With this setup it was possible to follow the flow pattern through many cycles, and establish thereby a more concrete basis for the theoretical study of non-steady compressible flow. A typical sequence of pictures obtained during a cycle is exhibited in Figure 11. Such observations also are focussing greater attention on the discontinuous jet aspects of the emerging stream.

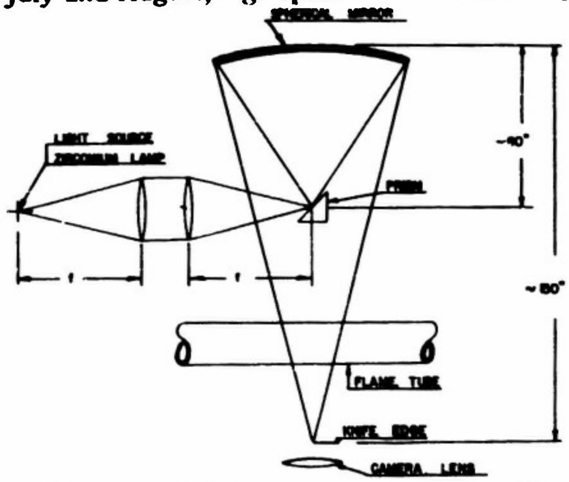


Figure 10. Schlieren diagram for a flame tube.

A general description of the flow pattern as seen in Figure 11 may be of interest. The Dynajet was operating at a frequency of about 230 c.p.s., the motion picture speed being 3300 frames/sec.

1. There is no evidence of regions of dead fluid.
2. The flow just outside the tube walls and some distance upstream of the exhaust end is at all times in the downstream direction with comparatively small velocity variations; the inclination of the flow to the axis of the tube increases with lateral distance.
3. A vortex ring is formed along the rim of the exhaust end, clockwise or counterclockwise according to the relative magnitudes of the flow inside and outside the jet. A necking is exhibited clearly at some stages of the cycle; the inner flow is then reduced in magnitude outward, or has reversed and is directed inwards.
4. The necking lasts for about ¼ of the cycle in varying magnitudes, and disappears gradually with increasing velocity of the inner

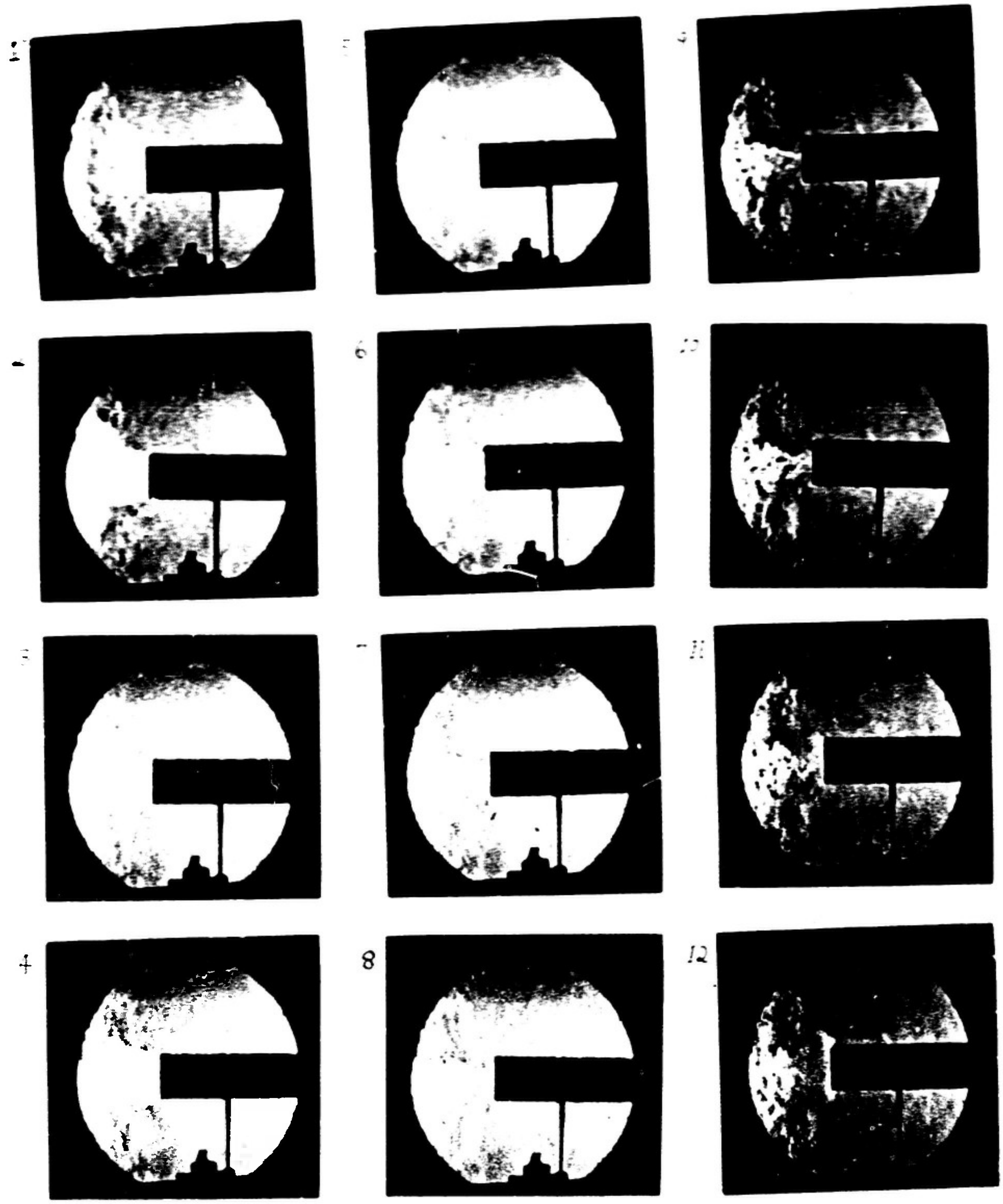


Figure 11. Schlieren photographs of gas motions from the exhaust end of the tailpipe of a Dynajet over a single cycle. Note the necking down of the jet beginning at frame 6 and the return flow beginning at frame 9.

flow. After it has disappeared, there are indications of a vortex ring along the rim in an outward direction.

Theoretical

Toward an Analytic Description of the Flow Pattern. Roughly speaking, the flow velocity corresponds very nearly to that of a quasi-steady pulsating jet, of the type $a + b \sin \omega t$, moving into a medium also pulsating with the same frequency but with a smaller amplitude and perhaps a phase lag. A bound vortex surface is set up at the rim of the tube, with a surface of discontinuity extending both upstream and downstream; this surface separates the flow originating inside the tube from that outside. The downstream discontinuity surface is fairly well defined at all times; it goes through periodic changes of shape and exhibits at certain stages of the cycle a characteristic constriction or "necking" in the plane of the rim of the tube. At these stages, the rim vortex direction is inward, the flow outside the tube is in the downstream direction, while the flow near the axis is either reduced appreciably or reversed.

Consequently, as was suspected earlier, the problem may not be treated entirely from the point of view of a vortex-free potential flow, even when heat and viscosity effects are left out of consideration.

It thus seems possible to synthesize any of the qualitative features of the emerging flow on the basis of two quasi-steady flows, one inside the other outside the tube, accompanied by a vortex surface of separation of vorticity roughly proportional to the instantaneous difference in the flow velocities.

Future Plans

It does not seem impossible to duplicate the overall aspect of the phenomenon and to build up its visible characteristics by a combination of mathematical expressions of reasonable character. Such an attempt is now in process. If this may be done and is confirmed by further experimentation of a more quantitative nature, proper boundary conditions will have been established for an extensive theoretical analysis of compressible fluids in non-steady flow.

QUARTERLY PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH

ON LIQUID ROCKET AND PULSE JET PROPULSION

FOR THE

BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

CONTRACT N6ORI-98, TASK ORDER II

POLYTECHNIC INSTITUTE OF BROOKLYN
BROOKLYN, NEW YORK
1 OCTOBER 1947

INTRODUCTION

Research work on Project SQUID at the Polytechnic Institute of Brooklyn has progressed smoothly during the third quarter of 1947. In addition to reasonable progress on the analytical attack of the various phase assignments, experimental preparations have advanced considerably. Test facilities, as mentioned in the previous progress report, have now been obtained on letter of intent. These facilities, which were built and instrumented for pulse jet testing, are located near Williamsport, Pennsylvania. Plans are going ahead for their actual occupancy and use.

One technical report of a theoretical nature was submitted to Project SQUID administrative headquarters in early September. The title of the report was *A Theoretical Investigation of the Temperature Field in the Laminar Boundary Layer on a Porous Flat Plate with Fluid Injection*, by Dr. Shao-Wen Yuan. The contents of this are described more fully under Phase 3 in the present report. Four additional technical reports are expected to be completed in the near future. Two of these reports deal with analytical work on Phase 1 and two on Phase 4.

Most of the research personnel on Project SQUID have been moved to a new building at 72 Schermerhorn Street, Brooklyn, where the second floor of a reasonably large building across the street from the previous facilities has been obtained. This arrangement will save a considerable amount of time and provide better working quarters.

The instrumentation program is progressing satisfactorily with the expansion of the experimental research program now underway on three of the phases. Since the instrumentation projects which have been inaugurated apply more or less to all four phases, a summary of the instrumentation program is given below.

Equipment for Strain Gauge Instruments. The proposed use of strain gauges for various fluctuating measurements requires the development of a carrier-type amplifier and phase-sensitive detector to drive the recording oscillograph. To obtain a high degree of stability and constancy of calibration, large amounts of negative feedback are used in the amplifiers. The phase-sensitive detector is of the balanced-modulator type, as is common in commercial practice.

Ultrasonic Pressure Waves. A method is being investigated for the instantaneous measurement of temperature in both steady and non-steady gas flow utilizing the variation of the velocity of ultrasonic waves with temperature. Because of the high frequency of the fluctuation of the gas temperature in pulse jets, and because it is desired to have many measurements per combustion period, ultrasonic waves must be used. This method will also produce a sharply defined pulse wave front, thus increasing the accuracy of the transit time measurements.

Since the temperatures involved approximate, and in many cases exceed, the Curie point of quartz and other piezo-electric crystals, magnetostriction transducer transmitters and receivers will be used. Transit time will be measured as the distance between two pips on the screen of a cathode ray oscillograph. A four-gun cathode ray tube will be used together with a recording camera; three guns for three points of measurement and the fourth as a timing axis.

The necessary electronic equipment to be used with this type of instrument is, in part, commercially available and will be ordered after the characteristics of the transducers have been determined. The remaining components will be built at PIBAL.

X-Ray Temperature Measurements. A description of the basic principles involved and some experimental results were reported in detail in the last quarterly report. The results to date show great promise for this method of local average temperature determination. It is proposed, therefore, to apply this technique to the measurement of the average wall temperature in pulse jets.

As intermediate steps, it is proposed to (1) duplicate the measurements on a sample of the specific material used in the pulse jet model to determine the most efficient X-ray source; and (2) to apply this information to measurements on a cylinder of similar dimension to work out mechanical details.

X-Ray Density Measurements. It is planned to continue work instigated roughly by German scientists on the absorption of X-rays as a function of gas density. Preliminary investigations will be carried out under static conditions. When facilities are available, the work will be extended to supersonic flow.

Hot-Wire Anemometry. The construction of the hot-wire anemometer as developed at PIBAL has been modified and improved. New fabrication techniques are being used. Some progress has been made on the development of a two-wire instrument for simultaneous measurements of temperature and velocity in a compressible flow as mentioned in the last progress report.

Several members of the staff visited various facilities and instrumentation companies. Mr. Paul Torda visited Dr. K. Wohl at the University of Delaware regarding some phases of the combustion problem associated with Phase 1. Messrs. Torda and Walter Weiss visited the Stromberg-Carlson Company in Rochester, the ITE Circuit Breaker Company in Philadelphia, the Crystal Research Laboratory in Hartford, and the Naval Research Laboratory at Anacostia, regarding components to be uxed on the instrumentation project as well as to discuss bids on the experimental pulse jet engines which are at present being manufactured.

PHASE NO. 1

In connection with pulse jet engines: to study the intermittent air intake process and the overall aero-thermodynamical mechanism of the pulse jet at subsonic and supersonic speeds. The study will cover theoretical and experimental investigation of (1) reciprocating and rotating valve mechanisms, (2) internally coupled pulse jets and related devices, and (3) such processes as may be necessary for the formulation of a unified pulse jet theory.

Summary

The results of the numerical evaluation of special and complete solutions of the differential equations representing the air inflow between moving reed valves show that under properly chosen conditions of design the reed valves move during the opening period without oscillation and that a smooth nozzle flow for the air can be achieved. The analysis of the aero-thermodynamical mechanism of the "idealized" case shows good qualitative agreement with experimental data. The test models for the experimental work on rotating sleeve valves for pulse jets are being built according to our shop drawings and will be finished shortly.

Progress

Air Inflow Analysis. The analysis for a compressible air inflow through hinged and clamped reed valves has been described in previous progress reports. Special reference should be made to PIBAL Report, *Resumés of the Research Progress and Proposals for Future Work under Project SQUID at the Polytechnic Institute of Brooklyn,* July 1947. It has also been stated previously that a method of integration of the non-linear partial differential equations, representing the air inflow, has been found and that special appropriate solutions have been investigated.

Since then a complete solution of the equations has been worked out in analytical and numerical detail. It yields free continuous motion of the reeds during the inflow as well as smooth nozzle-flow for the air. A considerable time has been spent on numerical evaluation of the results. The preparation of two technical reports has been progressing for some time. These reports will be submitted in the near future.

Aero-thermodynamical Analysis of Pulse Jets. The analysis of the overall aero-thermodynamical mechanism of pulse jets has been progressing along lines discussed in previous reports. The equations have been set up and the successive steps of their integration outlined. The integration has been made for the "idealized" case, i.e. a quasi-one-dimensional compressible gas flow with heat input and turbulent friction in a duct of constant cross section. A numerical comparison with experimental data shows good qualitative agreement.

Rotary Valves. Two test models of the pulse jet with rotating sleeve intake valves have been ordered from the ITE Circuit Breaker Company of Philadelphia. This company reported that the manufacture of the units has already been started. The first model, for air intake investigations without combustion, will be delivered within three weeks. Final machining of the second model for experiments with combustion will depend on the test results with the first model.

Plans

Future work will be directed towards the preparation of design charts for reed valves. A more complete analysis of the aero-thermodynamical process of pulse jets is planned taking into account radiation and heat convection. The investigations of air intake through rotating sleeve valves will be started as soon as the first test model is received.

Instrumentation

A more detailed description of the special instrumentation program under development at PIBAL is given in a section of the general introduction to this report. Only a brief summary of the instrumentation program, as related to Phase No. 1, will be given here. It is proposed to use dynamic strain gauge instruments for the continuous recording of momentary values of thrust and combustion chamber and tail pipe pressures.[1]

Average wall temperatures will be measured with thermocouples. The X-ray method of wall temperature measurement may also be used here.

Ultrasonic pressure waves will be used to give continuous record of the momentary gas temperatures averaged over the cross section.

Fuel and air flows will be measured by standard methods.

Multi-channel magnetic oscillographs and multibeam cathode ray tube oscillographs will be used for recording.

PHASE NO. 2

(1) To investigate causes of metal failure thus far encountered by evaluation of use tests on developed materials and (2) To investigate and develop new alloys to resist pressure, temperature and erosion conditions existing in propulsion units by (a) modificaton of present alloys, (b) development of new alloys, and (c) use of powder metallurgy methods.

Summary

The second experimental extensometer for the modified creep machines has been completed. Initial tests have been run on it and its predecessor.

The status of work on creep machines, dilatometer, and temperature studies is reported.

Some initial results of the carbide studies and of the Be-Cr system are outlined.

Progress

TENSILE TYPE TESTS:

Modified Creep Machines. Work is continuing on the construction of the modified creep machines. These will be used to study creep phenomena while the emperature of the specimen is varied. It has been decided to finish one machine first to determine whether the design of the second needs change. The first machine is complete except for the high-temperature alloy extension rods that apply the load to the specimen. These parts are to be completed shortly.

High-Temperature Extensometer. Two extensometers for use with the modified creep machines have been completed. These have been described and illustrated in the *Quarterly Progress Report* of 1 July 1947

The extensometers have been calibrated on a variable length tensile specimen. A Leeds and Northrup Micromax potentiometric recorder was modified for these tests. It has been found that the original design was substantially correct, although further work will be undertaken to develop higher sensitivity extensometers of lighter construction. Parts for permanent adaptation of the Micromax have been ordered.

Dilatometer. This instrument, which will furnish temperature-expansion corrections to the data of the creep machine, is approaching final assembly. The recorder has been modified so that the dilatometer will respond to thermal changes at a rate such as that encountered in a quenching operation.

TEMPERATURE DISTRIBUTION STUDIES. Three special alloy steels for these studies were received.

Preliminary experiments were performed on these alloys to determine their uniformity and response to the heat treating operations, and the effects of polishing and etching techniques.

The production of thermal standards under rigorously controlled conditions is progressing.

[1] To determine the usefulness of the strain gauge pressure indicators in terms of their frequency response, a calibration program is being developed. It is proposed to calibrate the gauges at various frequencies using both sinusoidal and "square-wave" pressure variations. A calibration run for varying temperature at stepped pressures will also be made. The results will be compared with those obtained from available pressure gauges of other types.

System Be-Cr. Great difficulty has been encountered in the study of this system. Common alloying practices are unsatisfactory. The refractory problem is one of the most difficult. Although beryllium melts at a relatively low temperature, its reactivity increases many fold at the higher temperatures required to alloy it with chromium.

A diffusion alloy sample of beryllium in chromium was prepared to indicate the microstructures to be encountered over a wide range of compositions. In this experiment a block of pure chromium was drilled partly through, leaving a cylindrical recess. This was filled with beryllium. The specimen was heated in an argon atmosphere for several hours at a temperature above the melting point of beryllium (1280 ± 40°C) but below that of chromium (1800 ± 50°C). Under these conditions the beryllium diffused into the solid chromium to a depth of about 3/16 inch. In the diffusion zone the composition ranged from 100% Cr, 0% Be to 0% Cr, 100% Be. Thus one specimen contained all the structures obtainable in this system.

This block was then sectioned to expose the diffusion zone and the surface was polished for metallographic examination. Several structures were revealed under the microscope. See Figures 1, 2, 3, and 4.

Hardness measurements were made across the diffusion zone and were found to be considerably higher than those of the pure metals.

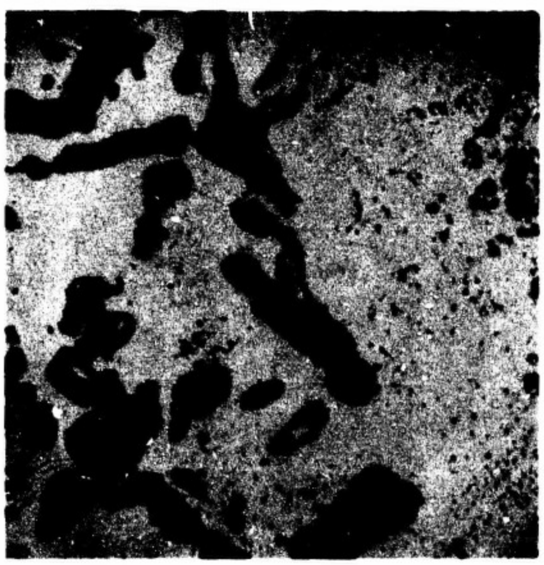


Figure 1. In the diffusion zone between Be and Cr, high Cr end. Unetched specimen. 500×.

Figure 2. In the diffusion zone between Be and Cr, intermediate zone. Unetched specimen. 500×.

Figure 3. In the diffusion zone between Be and Cr, high Be end. Unetched specimen. 500×.

CARBIDES AND NITRIDES. Melts of carbides with various refractory metals have been produced in the carbon arc. This method was used to determine the interaction of the various carbides with refractory metals under extreme temperature as a rapid means of qualitative classification. The percentages of refractory metals used were those calculated to fill the interstices of the carbide particles with refractory binder.

To prepare the beads for metallographic examination, it was necessary to use diamond dust as a cutting agent, due to the hardness of the beads. The polishing was done on lead laps im-

Figure 4. Same negative as in Figure 3. Higher contrast. Unetched specimen. 500×.

pregnated with the diamond dust. Etching was done in caustic potassium ferricyanide for ten minutes.

Figures 5, 6, 7, 8, and 9 show the structures of the beads at 1000× magnification. The structures reveal all gradations from a complete alloying, in the case of Figure 5, to practically no alloying as shown in Figure 7.

To investigate the more promising systems in a quantitative manner, an experimental carbon resistance furnace was constructed. Figure 10 is a schematic drawing of this furnace, in which high temperatures can be controlled. Fusion experiments are now under way using this equipment.

Figure 5. Carbide-metallic specimen, 86.11% WC, 13.89% Cr. 1000×.

Figure 6. Carbide-metallic specimen, 81.29% WC, 18.71% Mo. 1000×.

Plans

On completion of the tensile equipment, experiments will be started to determine the effect of rate of heating and cooling on creep.

When temperature standards have been produced, the temperatures of prepared samples will be determined from these standards as a check on the validity of this method. On completion of these experiments, practical tests of rocket chambers and parts can be undertaken.

Study of the system Be-Cr will be continued.

Quantitative treatment of various systems of carbides and refractory metals will be undertaken.

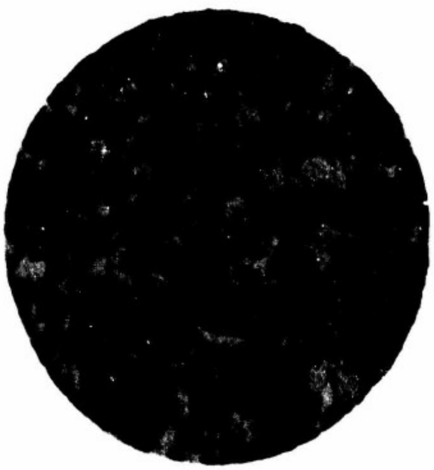
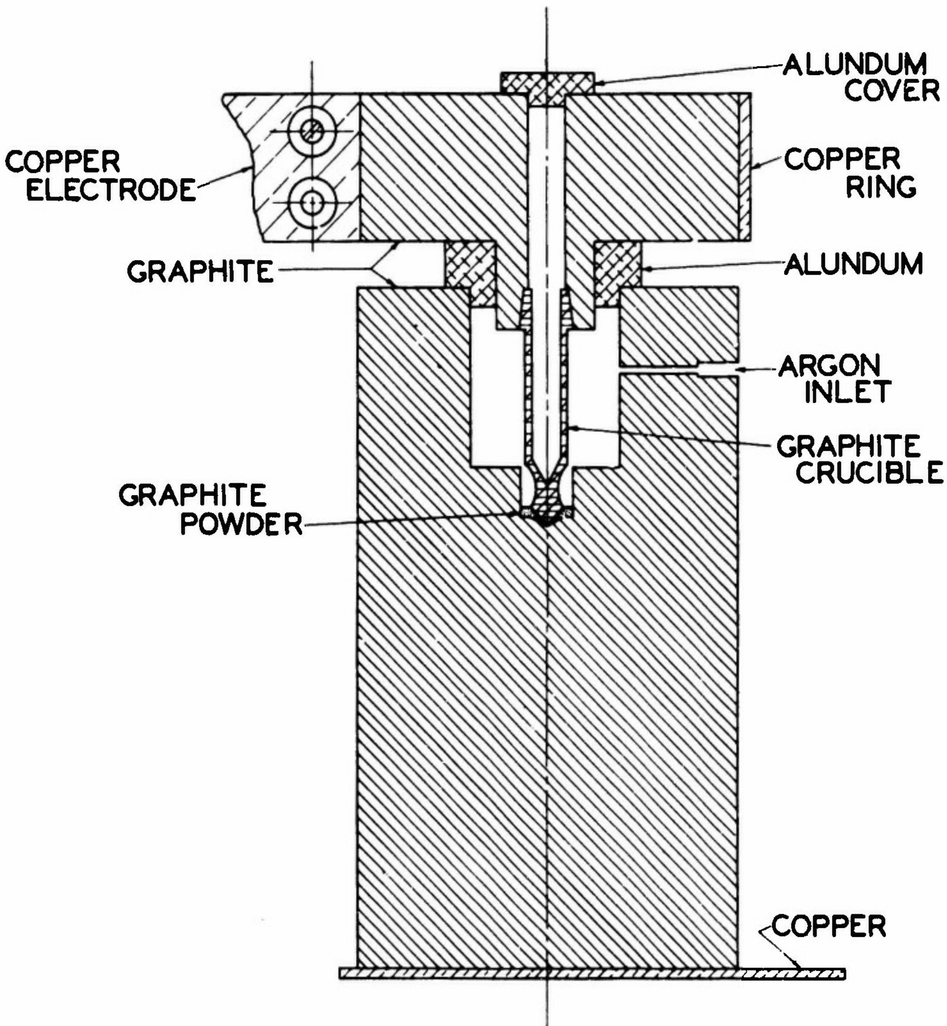


Figure 7. Carbide-metallic specimen, 83.28% WC, 16.72% Co. 1000×.

Figure 8. Carbide-metallic specimen, 62.2% TiC, 37.8% Cr. 1000×.

Figure 9. Carbide-metallic specimen, 56.91% TiC, 43.09% Co. 1000×.



RESISTANCE FURNACE

PHASE NO. 3

(a) To investigate the metallurgical, fabrication, and design problems involved in cooling rocket and intermittent jet motors by the diffusion of fluids through porous metal combustion chamber liners. (b) To study analytically and experimentally (1) the diffusion of fluids through porous media under high pressures and temperatures and (2) the effects (of this diffusion) on the internal aerodynamics. (c) To study problems in the field of physical chemistry pertinent to (a) and (b) with consideration given to the clogging of pores, the use of catalysts imbedded in the linear walls, and endothermic diffusion processes.

Summary

A theoretical investigation of the laminar boundary layer flowing along a porous flat plate with a fluid injected through the porous cells of the plate was presented in a technical report. Further work giving consideration to the compressible effect is in progress. An experimental setup to investigate the stability of the laminar boundary layer along the surface of a porous flat plate with injection is underway.

Progress

A technical report entitled *A Theoretical Investigation of the Temperature Field in the Laminar Boundary Layer on a Porous Flat Plate with Fluid Injection* was presented, and the contents of the report are as follows.

A theoretical investigation of the flow of hot fluid over a porous flat plate under the condition of uniform fluid injection from the bottom of the plate was made. The momentum equation and the corresponding energy equation for the boundary layer were set up with the velocity of injection assumed to be uniformly distributed along the plate.

In the solutions of the laminar boundary layer equation, the momentum and energy equations were reduced to the integral relation form similar to the Karman integral relation of the Prandtl equation. The velocity and temperature profiles were assumed as a polynomial of the fourth degree and also as an exponential function.

The solution of the above equations gave the relationship of the boundary layer thickness and of the temperature layer thickness in the boundary layer to a length in the direction of flow. The velocity profiles and the temperature profiles for different Prandtl numbers were then calculated. The solution was also extended to the case where the coolant injection begins at any known distance from the leading edge of the plate.

The relation between the wall temperature and the rate of coolant injection was calculated for different Reynolds numbers, Prandtl numbers, and for a partially extended porous plate. The curves are shown in the report.

The analysis for a compressible fluid in which the mass density and viscosity are functions of the temperature is in progress. These two parameters were assumed to be constant in the previous analysis.

An experimental setup to investigate the stability of the laminar boundary layer along the surface of a porous flat plate with injection has been prepared. As soon as porous flat plates are received, the tests will be conducted.

QUARTERLY PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH

ON LIQUID ROCKET AND PULSE JET PROPULSION

FOR THE

BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

CONTRACT N6ORI-104, TASK ORDER I

PURDUE RESEARCH FOUNDATION
and
PURDUE UNIVERSITY
LAFAYETTE, INDIANA
1 OCTOBER 1947

PHASE NO. 2

To study continuous process combustion, defining effects of combustion-chamber size and shape, fuel and oxidizer distribution, and turbulence with available fuels and oxidizers. Project leader, H. J. Buttner, Professor of Automotive Engineering.

Summary

In general, the activities for this period can be grouped in the same four phases as reported in the *Quarterly Progress Report* of 1 July 1947, namely: (1) the creation and measurement of turbulence in a small-scale Bunsen-type burner and observation of the effects of turbulence on combustion; (2) the investigation of the factors involved in flame holders of new design; (3) modification and improvement of the intermediate-sized burner; (4) and planning, procuring, and constructing the equipment and facilities for large-scale combustion studies.

A number of new designs of contracting jet nozzles were fabricated for the Bunsen-type burner test and a study of the effect produced on the nature of the flame was made.

Numerous photographs were obtained of the flames from one of the newly designed burner in an attempt to obtain optimum magnification and clarity. A study was made of the effect of the rotating rod in the axis of the contracting jet on the area of the flame front.

Several precision modifications of the annulus type of flame holder were fabricated and tested.

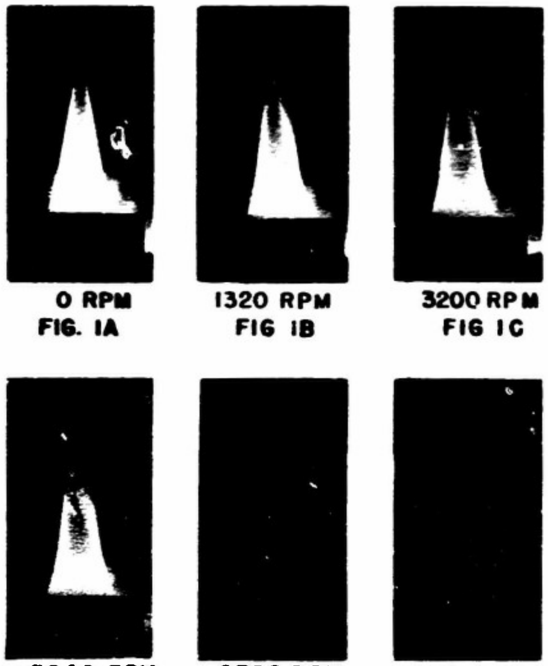
The combustion laboratory building has been completed except for electrical wiring. A large part of the equipment has been moved into this laboratory and is being rapidly installed.

Progress

Considerable instability has been encountered in the new hot wire anemometer d-c amplifier. This has prevented any measurement of intensity of turbulence during this period of research. Activities on the Bunsen-type small-scale burner have therefore been concentrated on developing methods for photographing and measuring the flame front obtained with different combinations of contracting-jet nozzles and speeds of rotation of the turbulence-creating rotating rod described in the 1 July 1947 *Quarterly Progress Report*.

Several different photographic methods, including the schlieren method, were tried to obtain optimum amplification and clarity of the photographic reproduction of the flame. The most successful reproductions were obtained using an Agfa Compur camera with an F4.5 lens and Ansco Iso-Pan film. Four reproductions using this combination are shown in Figures 1a to 1d inclusive. Figures 1e and 1f were made using Eastman XX film. Enlargements of 10 to 1 permitted determination of the flame area in accordance with methods described by Garside, Forsythe and Townend.[1]

FIG. 1



0 RPM FIG. 1A | 1320 RPM FIG 1B | 3200 RPM FIG 1C

5940 RPM FIG 1D | 6750 RPM FIG 1E | 7280 RPM FIG 1F

Figures 1a to 1f show the pictures obtained with the turbulence-creating rod stationary and also rotating at five different speeds.

Figure 2 shows a plot of the area of the flame fronts at the various speeds. The multiple cone effect, most apparent in Figure 1d, is believed to be due to oscillations in the rod and slow shutter speed of the camera. However, measurements of the areas of several of these cones in any photo-

[1] J. E. Garside, J. S. Forsyth, and D. T. A. Townend, The Stability of Burner Flames, Institute of Fuel, August 1945, p. 175.

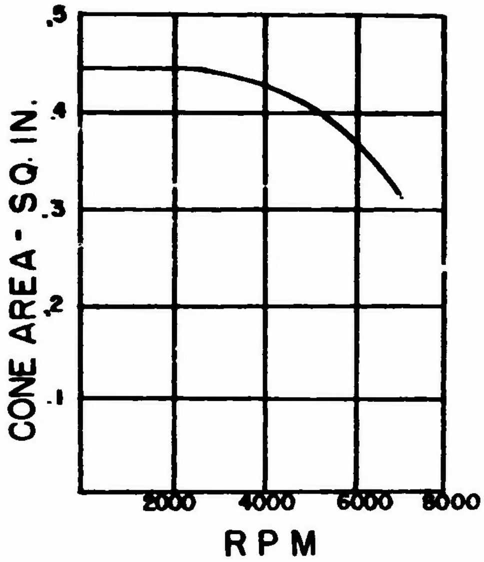


Figure 2.

graph show a deviation within two per cent, which is within the limits of accuracy of measurements necessary for the area determination.

From Figure 2 and from previous measurements of intensity of turbulence reported in the 1 July 1947 *Quarterly Progress Report,* there seems to be a measurable relation existing between turbulence, flame speed, and the rotating rod speed (the latter imparting the turbulence).

Inversion of the flame tip was not photographed due to the extreme sensitivity of the flame when all conditions were correct for the inversion. Arresting the inversion before completion of the travel of the tip to the extremity of the rod presented a problem.

Numerous experiments were conducted with the annulus-type of flame holder. Many modifications were made to reduce turbulence to a mini-

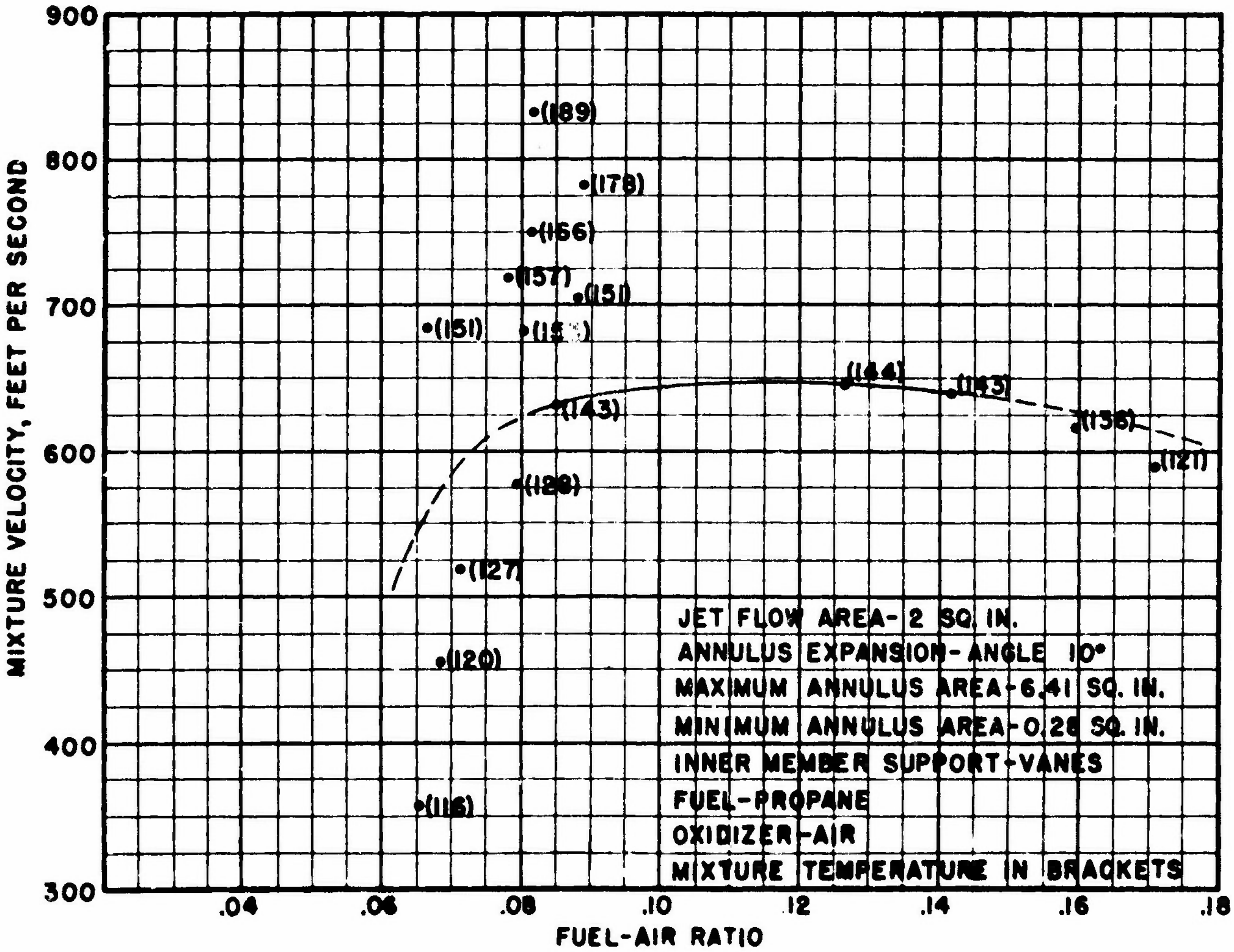


Figure 3. Mixture velocity in contracting jet burner at flame blow-off point.

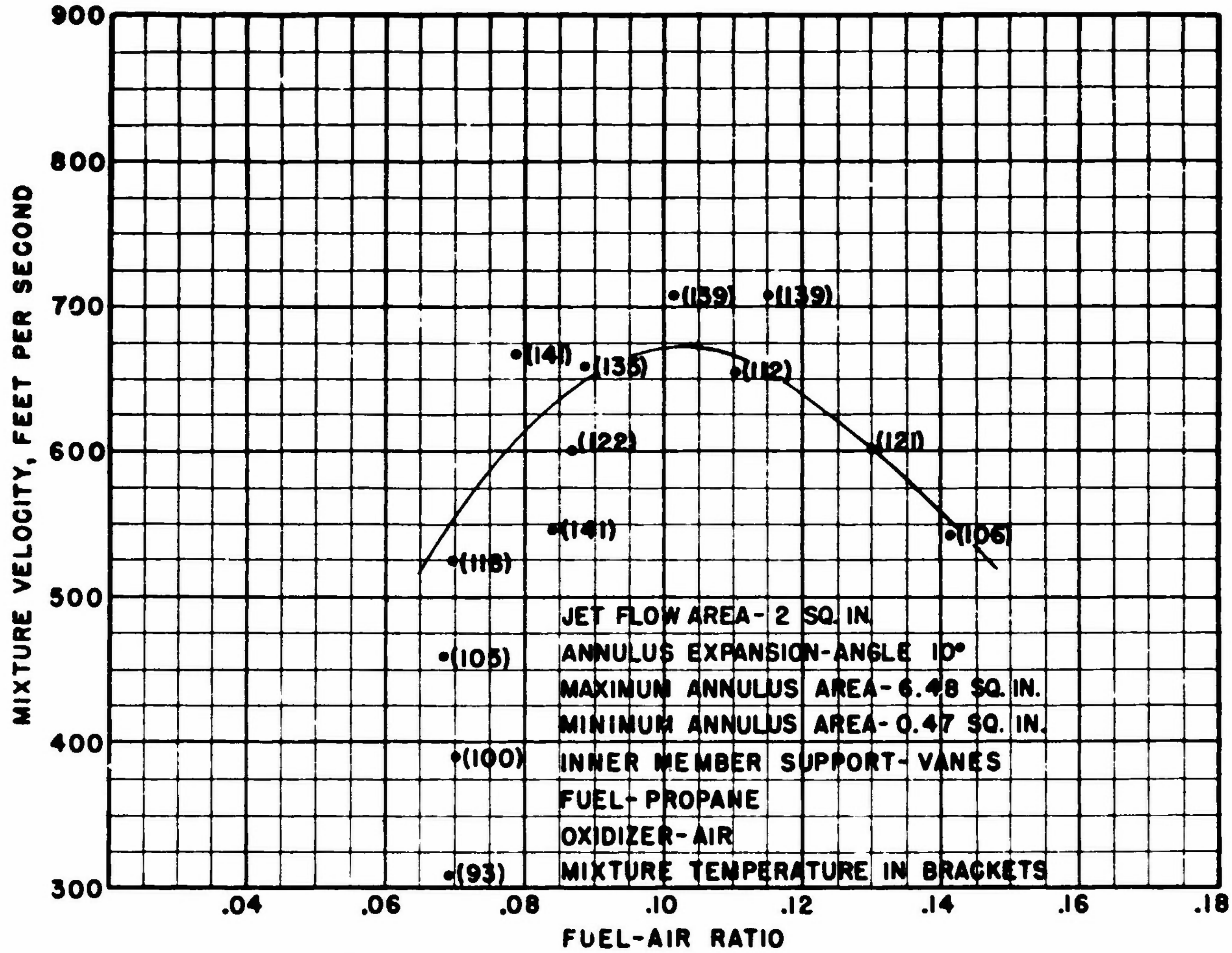


Figure 4. Mixture velocity in contracting jet burner at flame blow-off point.

mum in the annulus and to prevent any general movement of the fuel-air mixture other than axial. Flame retention in the annulus with mean mixture velocities of 37 feet per second were obtained under turbulent conditions. The main body of the mixture in the central contracting jet was 835 feet per second. Under these conditions 15 per cent of the total mixture supplied passed through the annulus. A very steady flame was encountered up to these velocities and the mixture was readily reignited from a spark gap inserted in the annulus. A reduction of turbulence through removal of the locating vanes used for positioning the inner member and maintaining concentricity of the annulus caused the flame in the annulus to position itself axially at a point where the mixture velocity equalled the spatial velocity of the flame.

Figures 3 to 5 show the contracting-jet mixture velocities obtainable at the point of flame blow-off. The only difference in the three setups, is the area of the annulus at the entrance. The highest mixture velocity was obtained at the minimum annulus opening which gave an area 14 per cent of the minimum jet area. The temperature of the mixture was not controlled in these runs and the very appreciable effect of temperature variation can be seen from the points on the curves. Later runs with mixture temperature controlled were made, but data are insufficient for presentation at this time. However the trend of the solid line in Figure 3 is substantiated.

The new Combustion Laboratory building at the Purdue University Airport has been completed sufficiently to permit partial occupancy, but electrical power for lighting and other uses is not available. Installation of equipment and engines has been started.

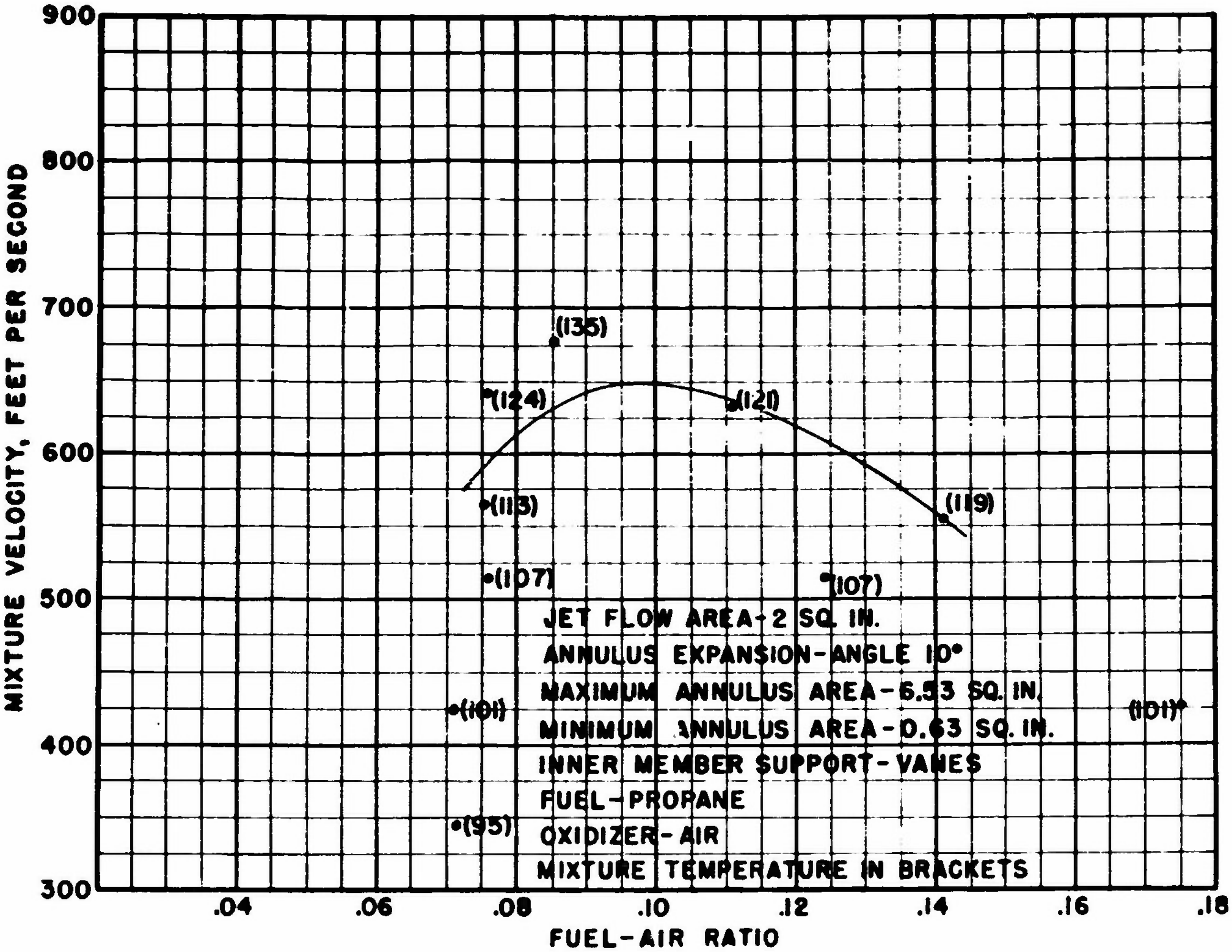


Figure 5. Mixture velocity in contracting jet burner at flame blow-off point.

Plans

With the addition of a full-time physical chemist and a full-time technician on October 1 supplementing two full-time and three half-time employees, the research program can be accelerated. It is planned to continue experimentation at the present location in the Mechanical Engineering Laboratory until the new laboratory is in full operation.

It is hoped that the research work can be expanded to cover other problems in line with the intent of this Project. The two phases of research previously discussed in this report will be intensively investigated with new techniques being developed. Completion of the hot-wire anemometer will permit more accurate analysis of the effects of variables now being studied.

PHASE NO. 3

This phase undertakes the study of corrosion in connection with jet propulsion. The purpose of the research is to identify the corrosion products, to investigate the process of corrosion and its dependence on the chemical and physical properties of the materials and on the conditions of exposure. Project leader, H. J. Yearian, Professor of Physics.

Summary

The oxidation of an 11% chromium-iron alloy has been studied at 640°C. The oxidation is erratic and non-uniform. It has not yet been possible to establish a correlation between this behavior and the polishing technique used. Whenever quantitative measurements have been possible, the data indicate the formation of a chromium-rich oxide with a subsequently less rapid oxidation of chromium than of iron.

X-ray diffraction of the oxide gives the structures of αFe_2O_3 and one of the magnetic oxides, Fe_3O_4 or γFe_2O_3. No chromium oxides or certain mixed oxides are found.

Electron diffraction of the surface during oxidation at 500°C shows the first oxide formed is Fe_3O_4 (or γFe_2O_3) and that αFe_2O_3 (or Cr_2O_3) appears later. At 600°C the first oxide is Fe_3O_4 and later, only Cr_2O_3 (or αFe_2O_3) is found on the surface.

Progress

An 11% chromium-iron alloy (11.45% Cr, 0.05% C, 0.00% Si, N analysis not complete) after homogenization at 2300°F has been recrystalized by α—γ transformation to give a sufficiently small grain size for the observation of oxide growth by the X-ray absorption method described in previous memoranda and reports.

The measurements have been hampered by the formation of a non-uniform layer, the thickness of which increases near the edges of the specimen. As oxidation proceeds this layer encroaches upon the region of measurement. Careful rounding and polishing of the specimen edges has reduced this difficulty but has not eliminated it. The data shown in Table I are thought to be free from such effects, but they must be considered as tentative. As in previous reports, the last column gives the amount of iron in the oxidized layer found by an interpolation method which is independent of assumption regarding the form of oxide present.

These samples (Table I) show widely different degrees of oxidation resistance. As previously found, the more resistant layers are the semitransparent ones showing yellow to brown color. The gray layer of similar thickness is less protective. Even the third sample shows as high a rate of attack as the 18% Cr-steel studied earlier at 900°C (*Quarterly Progress Report*, 1 July 1947). There is, as previously, some indication of approach to a constant amount of chromium in the oxide layer.

The thicker of these layers give only weak X-ray diffraction patterns on the Phillips spectrometer. Two components are found. One has the structure of αFe_2O_3, the second that of either Fe_3O_4 or γFe_2O_3. In a weak pattern the latter two are nearly indistinguishable.

Some of the heavier scales formed under similar conditions, have been removed and examined by conventional semi-precision Debye-Scherer X-ray methods. The results confirm those indicated by the Phillips spectrometer. The patterns of αFe_2O_3 and either or both of the magnetic oxides Fe_3O_4 and γFe_2O_3 are found. The lines of the latter two patterns, which are resolved from those of αFe_2O_3, differ by less than the discrepancies in the data published for the gamma form. Distinction between the two cannot be made, therefore, until more precise data are available. The chromium may be present in the oxide either in solid solution or in the form of $FeO \cdot Cr_2O_3$, which can hardly be distinguished from Fe_3O_4. The pure oxides of chromium, as well as $3\ Cr_2O_3 \cdot Fe_2O_3$, $Cr_2O_3 \cdot Fe_2O_3$ and probably $3\ Fe_2O_3 \cdot Cr_2O_3$, can be eliminated.

Micrographs of sections of these coatings show a single rather homogeneous layer, in contrast with the oxide on a 4% Cr-Fe alloy which has three layers similar to those formed on iron.

The surface structure of the 11 per cent Cr-Fe alloy has been examined by electron diffraction during oxidation at 500°C in an oxygen atmosphere at a pressure of 1 cm. of mercury. The photographs were taken by periodically exhausting the gas but without cooling the specimen.

With the limitations of interpretation as mentioned previously, the data as shown in Table II indicate that the oxide first formed at either temperature is "Fe_3O_4" For the thicker layers, the surface structure at 500°C is similar to that found

Table I

Oxidation of 11% Chromium-Iron by Oxygen at One-Atmosphere Pressure

Sample	Temp. °C	Time (Minutes)	Nature of Oxide	Cr, %	milligrams/cm² Total Oxide	Cr	Fe
$11E_1A$ ……..	640	10	gray, rough	26	0.33	0.087	0.15 (0.15)
	640	+20	gray, rough	9.6	0.74	0.071	0.44 (0.46)
$11E_1B$ ……..	640	15	yellow-green	8.4	0.14	0.012	0.088 (0.095)
	640	+20	gray, rough	8.0	0.41	0.033	0.26 (0.25)
	640	+20	gray, rough	19.5	1.01	0.20	0.51 (0.51)
$11E_2A$ ……..	640	10	yellow, smooth	10.8	0.36	0.039	0.21 (0.21)
	640	+20	yellow, smooth	13.2	0.48	0.064	0.27 (0.27)
	640	+90	brown, smooth	30.0	0.63	0.19	0.25 (0.24)
	640	+120	brown-gray	26.0	0.72	0.19	0.31 (0.32)

in bulk by X-ray methods at 640°C, but at the comparable temperature of 600°C the evidence for the surface structure favors Cr_2O_3 rather than αFe_2O_3. Differentiation between these patterns by reflection electron diffraction methods is difficult, but an attempt is being made to improve the technique sufficiently so that this can be done.

The cause of the erratic oxidation resistance of the alloy has been investigated, so far without conclusive results. These samples were prepared with a metallographic polish followed by an etch to remove polishing debris and flow layer. Quantitative absorption measurements on the same specimens prepared with various types of abrasive polish, but without an etch, fail because the X-ray intensity from the base metal changes during the oxidation treatment, apparently due to recrystallization of flow layer material. From the qualitative appearance of the oxides formed, no correlation has been found between protectiveness and type of polish or rate of initial heating. Electrolytic polish and etch methods will be investigated.

Table II

Surface Structure Study of 11% Chromium-Iron Alloy

Exposure	Structure
Original polish	αFe + trace Fe_3O_4
In vacuum at 500°C	$\alpha Fe + Fe_3O_4$
1 min., 1 cm. Hg, 500°C	Fe_3O_4
5 min., 1 cm. Hg, 500°C	Fe_3O_4
30 min., 1 cm. Hg, 500°C	Fe_3O_4
60 min., 1 cm. Hg, 500°C	$Fe_3O_4 + \alpha Fe_2O_3$ or Cr_2O_3
In vacuum at 600°C	αFe + unidentified pattern
1 min., 1 mm. Hg, 600°C	Fe_3O_4
5 min., 1 mm. Hg, 600°C	Cr_2O_3 (or αFe_2O_3)
30 min., 1 mm. Hg, 600°C	Cr_2O_3 (or αFe_2O_3)
60 min., 1 mm. Hg, 600°C	Cr_2O_3 (or αFe_2O_3)

Plans

Efforts to isolate the factors influencing the erratic oxidation resistance will be continued, as will the X-ray and electron diffraction measurements at temperatures of 640°C and higher. Improvements in both techniques which will permit better differentiation of similar structures will be sought. The program will be applied to binaries of higher purity whenever these become available, and will be extended to include commercially available alloys.

Examination of the oxide layer structure by optical and electron microscope methods will be intensified. Construction of the low-power electron microscope, previously discussed, for investigation of the distribution of chromium and iron in the oxide layers will be started.

PHASE NO. 4

The purpose of this research is to study, by means of bomb or continuous-flow experiments, temperatures, pressures, and concentration of reactants for various oxidation reactions of materials that may be of value as fuel for a rocket or jet engine. Project leader, D. E. Holcomb, Assistant Professor of Chemical Engineering.

Progress

The preliminary plan of research of this phase was to apply a flow method to the study of the explosive region of combustion of a fuel by carrying out a continuous explosive combustion reaction in a small combustion chamber and by sampling the reaction products at various time intervals by quenching the combustion gases with a stream of inert gas. This method presents a more direct approach to the problem of reaction velocity than the previous methods of studying reaction velocity by relating it to flame velocity. Qualitative tests have shown that a uniform combustion zone could not be maintained in a tube; hence no relation of time of reaction with the distance the gases had traveled in the tube could be established. Furthermore, the tests revealed that the zone of rapid reaction, i.e. the flame front, was so thin that it could not be sufficiently elongated at velocities possible in the combustion tube to make it possible to partially quench the reaction by an inert gas stream. The only part of the combustion zone in which the reaction could be stopped by this method was in the section of after-burning where the reactants were so spent that the reaction was progressing relatively slow.

This dynamic method for the study of reaction velocity holds promise for studying the fast reaction just below the explosion limit. Before it can be successfully applied, however, it is necessary to conduct studies by other means in the region of slow combustion because, first, the reaction mechanism and the intermediate products are related in the two cases and, second, it is necessary to determine the conditions that lead to explosion before dynamic method equipment can be designed.

During this quarter, work has been done on the construction of equipment suitable for carrying out the initial stages of the investigation of the slow combustion region of the reaction between hydrazine and oxygen. Slow arrival of pieces of apparatus which had been ordered have delayed completion of the assembly. All overdue orders are being expedited. Some of the equipment has been redesigned in order to eliminate "dead" space in the reactor. All the necessary pieces of apparatus for heating the oil bath, except the relay, have arrived and are in the process of being assembled. The reactor and the oil bath surrounding it have already been erected.

It is expected that initial experimental runs will be made during the next quarter.

Plans

The present plan calls for the study of the region of slow combustion using hydrazine as a fuel. This study will be conducted as follows:

a. The investigation of the effect of surface upon the reaction rate by varying the surface to volume ratio and following the reaction by measuring pressure rise to determine the homogeneous and heterogeneous parts of the reaction.

b. The investigation of the effect of concentration of reactants upon the rate of reaction.

c. The effect of change of pressure and temperature upon the reaction rate.

PHASE NO. 5

The purpose of this research is to determine, for liquid-fuel rockets and pulse jet engines, the radiation factor and its contribution to heat transfer coefficients inside a pipe with gas flow at low and also high temperatures. Project leader, J. M. Smith, Associate Professor of Chemical Engineering.

Summary

The cooler-condenser and the heaters were completed and installed. Preliminary tests were conducted to determine the maximum temperature attainable. The capacity of the heating coils was found to be insufficient and new heating units have been designed and materials ordered.

Progress

During this period the cooler and condenser for the hot exit gases were completed and installed. Tests conducted on the apparatus indicated that the capacity of the cooler was adequate. The remaining parts of the temperature recorder-controller unit were received and installed.

It was found by later considerations that the flow rates originally estimated to be necessary must be increased by a factor of 2 or 2.5 to give the desired Reynolds number at the required high temperature. Flow rates suitable for the experiments are available, but the heaters installed during this period were found to be of insufficient capacity to raise the necessary quantity of gas to the desired temperature. As a result of trial tests with these heaters, it was found that at a Reynolds number of 3680 the maximum air temperature entering the test section was 1750°F; at a Reynolds number of 8310 the temperature was 1594°F.

Since a maximum temperature of 2000°F is desired, it was decided to redesign the heaters using the foregoing data as a basis in the considerations. A new wire size has been chosen and the necessary materials have been ordered.

During this quarter it became evident that the air compressor in the Chemical and Metallurgical Engineering Building was of insufficient capacity to supply air for both this project and the other requirements in the building. It has been proposed to replace the present motor with one of larger rating. No change has been made as yet, but action by the Physical Plant of the University is expected soon.

A series of thermocouple shields have been designed for the purpose of eliminating the radiation error in pyrometer readings. Cost estimates and availability of the platinum tubing necessary for the construction of these shields are being made.

Plans

In the next quarter it is planned to fabricate and install the new heaters along with the necessary controlling equipment including the thermocouple shields in the test section. After the thermocouples and shields are installed, the apparatus should be ready for experimental tests.

PHASE NO. 6F

The purpose of this research is to determine experimentally heats of formation and combustion, the specific heats, and other thermodynamic properties of various fuels and oxidizers used in pulsating jet engines. If possible, a correlation of thermodynamic properties of these fuels will be made, so that calculations may be extended to include new fuels. Project leader, D. E. Holcomb, Assistant Professor of Chemical Engineering.

Summary

The original design of the calorimetric assembly ha.. proved unacceptable for use in determinations of heats of combustion with a precision of 0.1 per cent. The difficulties encountered were primarily due to poor design of the Emerson calorimetric apparatus obtained for the investigation.

Several of the nitroparaffins to be used in this investigation have been prepared and purified. Heats of formation of these substances will be started during the coming quarter.

Progress

The difficulties which arose in the experimentation using the Emerson calorimetric apparatus described in the previous reports have been remedied by incorporating the following changes in the apparatus assembly.

a. The installation of a stirrer in the outside calorimeter jacket in order to prevent stratification due to temperature differences within the jacket.
b. Substitution of a Parr bomb (Illium) for the original Emerson bomb (stainless steel) to facilitate rapid opening and closing of the bomb and as a precaution against corrosion (no lining is being used).
c. Redesign of the calorimeter can which provides a more uniform air space, complete immersion of the bomb, and more efficient stirring of water in the can.
d. Redesign of the calorimeter cover to insure metal-to-metal contact between the cover and the outer jacket.

These changes are nearing completion and calibration runs are about to be resumed.

Samples of nitromethane, nitroethane, 1-nitropropane, 2-nitropropane, 1,1-dinitropropane, and 1,2-dinitropropane have been prepared and purified to about 99% purity. Other dinitroparaffins are being investigated, but their preparation is being delayed by late delivery of an essential reagent (trimethylene bromide).

Plans for an automatic control of the temperature difference between the inner and outer water baths have been temporarily abandoned. Manually operated controls will be used.

Plans

The plans for the immediate future are to complete the calibration of the equipment and to determine the heats of combustion of the above compounds.

PHASE NO. 6G

The determination of heats of combustion of various chemical compounds suitable as high-energy fuels and oxidizers. Project leader, H. Hunt, Professor of Physical Chemistry.

Summary

The heats of combustion of methyl nitroacetate, 8-hydroxyquinoline, and 3-nitro-p-toluidine have been determined. Additional compounds have been purified and prepared for combustion. Recent attention has been directed toward various derivatives of hydrazine, several of which are in the process of purification and others, perhaps of greater promise, are being secured.

Progress

Experimental work on the determination of the heats of combustion of methyl nitroacetate, 8-hydroxyquinoline, and 3-nitro-p-toluidine have been completed. The temperature rise values in terms of microvolts per gram of sample burned indicate that a precision of five parts in 10,000 has been obtained. The values of the heats of combustion of these compounds will not be reported until a series of determinations have been concluded, probably at the time of the next quarterly report.

Four other compounds have been purified and prepared for combustion studies. These are, ethyl-p-aminobenzoate, p-aminoacetophenone, 5-nitro-o-toluidine, and p-phenylenediamine. The last mentioned of these compounds in an isomer of phenylhydrazine and inasmuch as attention is being focused on various derivatives of hydrazine as possible high energy fuels or oxidizers, this compound will be investigated. Several hydrazine derivatives, oxalylhydrazide, p-nitrophenylhydrazine and benzyl-phenylhydrazine have been obtained and are now being processed preparatory for the combustion studies.

In an effort to obtain other hydrazine derivatives which show promise of being useful as high energy fuels, Dr. Audrieth of the University of Illinois and Dr. Warner of Western Cartridge Company have been contacted as a possible source of supply.

Plans

Future work will consist in a continuation of the measurement of heats of combustion of selected substances, especially those believed to be potential high energy fuels or oxidizers.

PHASE NO. 7

Investigation of rocket motors and liquid propellants at high chamber pressures. Project leader, M. J. Zucrow, Professor of Gas Turbines and Jet Propulsion.

Summary

Detailed specifications for the rocket test pits have been completed. The equipment and instrumentation needed to conduct this research are being investigated and some of the materials have been ordered.

Progress

One full-time research fellow and two part-time research fellows are actively engaged in the preliminary studies, design. specifications, and ordering of equipment.

The detailed specifications for the rocket test pits have been completed. Final revisions are being incorporated in the test pit plans. It is estimated that the plans and specifications will be advertised for bids not later than October 24, 1947.

The propellant flow and transfer systems are being designed to meet the requirements of a maximum thrust of 2000 lbs. for 30 sec. at a maximum chamber pressure of 3000 p.s.i.a. The instrumentation is being investigated. A half-time chemical research fellow is investigating the chemical equipment required for the project.

Plans

It is hoped that all preliminary studies will be completed in the next quarter so that by the time the rocket test pits are completed, a full-scale research program can be quickly undertaken.

QUARTERLY PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH

ON LIQUID ROCKET AND PULSE JET PROPULSION

FOR THE

BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

CONTRACT N6ORI-119, TASK ORDER I

CORNELL AERONAUTICAL LABORATORY
BUFFALO, NEW YORK
I OCTOBER 1947

PHASE NO. 1

In connection with pulsating jet engines: to undertake theoretical and wind tunnel investigations on flows and losses in diffuser inlets, diffusers, intake valves, exhaust nozzles, and thrust-augmenting ducts for subsonic and supersonic pulsating jets.

Summary

In studying problems of non-stationary gas motion the method of characteristics was employed and some new procedures were developed. This study is being continued and at the same time the method is being applied to specific problems. A water table was built to study unsteady gas motion by means of the analogy with surface gravity waves. Experimentation is in progress to develop suitable means for recording variations of the depth of the water. Preliminary experiments with a free-piston pulse jet (represented by a tube mounted to a loud-speaker) were carried out and a surprisingly large thrust was observed when the tube was partly closed by an aperture plate.

Progress

The characteristics method of solving problems in one-dimensional linear gas motion was studied and applied to gas flow in pipes of discontinuously varying cross section. The methods available from various reports were replaced by a new method which permits the necessary trial and error procedure to be carried out more rapidly and more accurately. The method of dealing with weak shock waves was also improved. The reflection of waves from constricted end sections is now being considered, but a satisfactory solution has not yet been found.

The characteristics method is also being applied to the study of a pulse jet with a system of externally operated valves. By proper interception

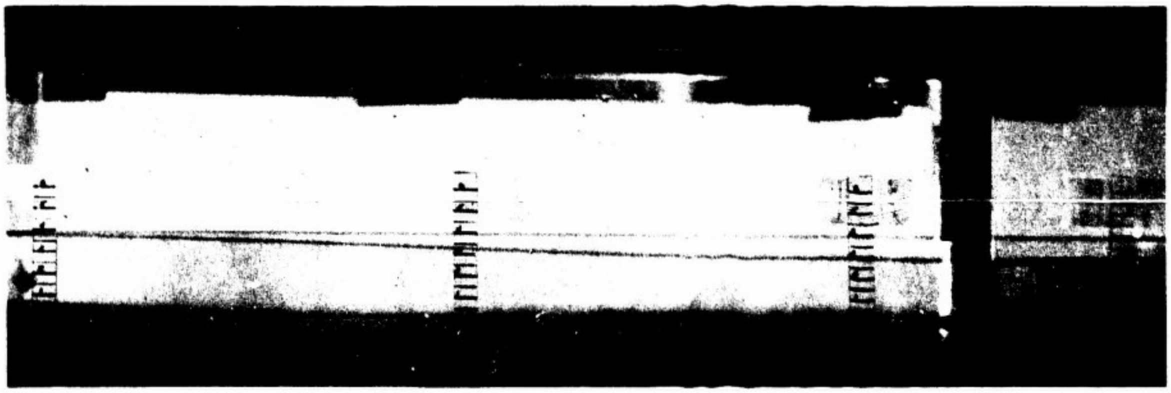


Fig. 1. Photographic record of water waves. One exposure taken before opening of channel gate and a second exposure on same film taken about one-half second after opening.

and transmission of expansion and compression waves, it is hoped to improve the performance of the jet.

A water table to study the analogy of surface gravity waves and gas waves in ducts has been completed. It consists essentially of a test channel, 2 feet long and 6 inches wide, connected to a large basin that is 4 feet by 4 feet. It is made entirely of lucite so that both vertical and horizontal observations may be made. The gate to the channel entrance is opened by releasing a weight suspended over a pulley. While closed, the gate is kept water-tight by two small electromagnets which produce sufficient closing pressure. At the instant of opening, the current through the magnets is interrupted. If this channel is filled with water to a higher level than the outside basin and the gate is suddenly opened, an experiment is performed analogous to the expansion of compressed air from a tube when one end is suddenly opened. When the channel was illuminated by diffuse light from one side, the level could be photographed from the other side and a good picture of the wave form obtained. Fig. 1 shows such a photograph where two exposures were taken on the same film, one before opening of the gate and the other about one-half second after opening. To take a whole series of such photographs on the same film would make a proper identification of lines impossible, and a change of film or shift of the image would be necessary after every four or five exposures. Since the accuracy of this method of depth determination seems to be limited by the smallness of the photographic record, different methods are being investigated. Coloring the water and measuring the light absorption by means of a photoelectric cell appears possible, but the sensitivity reached so far has not been satisfactory. A very simple arrangement to measure depth by recording the electric resistance between two submerged electrodes gave very promising results and is being investigated further.

An experiment to measure gas expansion in a tube directly by measuring the light absorption in a smoke-filled atmosphere was tried. It was found that the sudden expansion following the breaking of the closing membrane produced spurious effects on the optical system. However, this experiment has been temporarily suspended because of lack of personnel.

Experimentation was started on the free-piston pulse jet (Bodine jet). For the first experiments, a 2-foot tube 4 inches in diameter was mounted on a small loud-speaker whose membrane acted as piston. The other end of the tube was left open. When suspended, this system seemed to develop some thrust which, however, was too small to be measured. Injection of smoke showed definite jet formation and tests with different tubes showed that jets were always formed at resonance frequencies. This was established by introducing cork powder into the tube and observing the pattern formed. The loud-speaker was completely enclosed to eliminate any valve action of the membrane, but the phenomena remained essentially unaltered. When the open end was partly closed by means of an aperture plate, a very strong jet was formed. The tube, 12 inches long, was suspended on a beam carrying a strain gauge and it was now easily possible to measure the thrust developed. The electrical power input to the

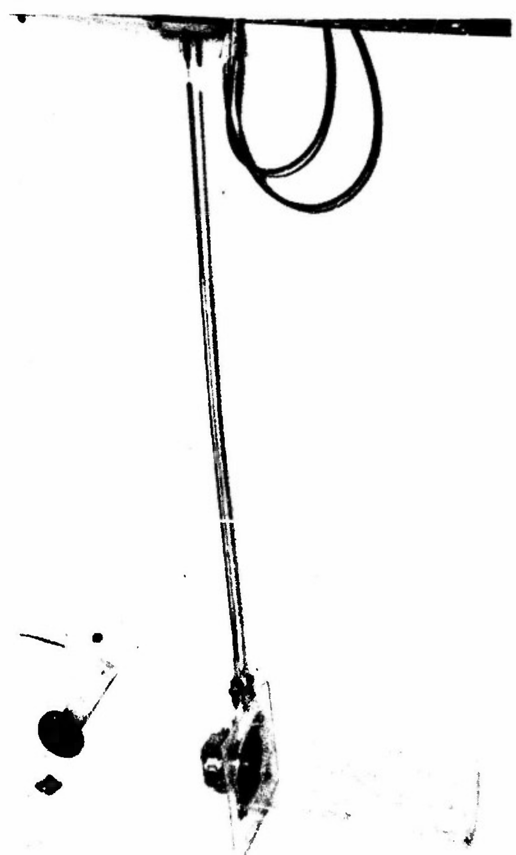


Fig. 2. Setup of free piston pulse jet experiment.

loud-speaker was also measured by measuring voltage current and power factor (by means of a cathode-ray oscillograph). The thrust measured per watt input was converted to specific impulse in seconds (pounds of thrust/pounds of fuel per second) in order to obtain a comparison with ordinary pulse jets. The conversion was based on an energy release of 19,000 Btu per pound of fuel. The specific impulses thus obtained were of the order of 40,000 seconds as compared to about 1400 seconds for ordinary pulse jets. This value seems enormous even after allowing for the fact that 100 per cent thermal efficiency was assumed in the conversion, and careful further investigations will have to be carried out to verify this result. The experimental set up is shown in Fig. 2. The thrust developed depends on the size of the aperture and also on the frequency. For all aperture plates, the thrust versus frequency curves show two distinct maxima, one near the resonance frequency of the half-open pipe and the other one at about one-half of this frequency.

Plans

Experiments with the free-piston pulse jet will be continued to examine the validity of the results found so far and to find the optimum operating conditions. It is also intended to build a small model with an oscillating piston driven by an electric motor. An attempt will be made to explain the results by means of the characteristics method. After solving the instrumentation problems for the water-analogy experiments—instantaneous recording of depth and, if possible, an independent method to measure flow velocities—the water table will be used to study the operation of a free-piston pulse jet. Experimental results obtained with this setup will be compared with theoretical results obtained by both the characteristics method and the analytical method for pipes of various shapes reported previously.

PHASE NO. 2

In connection with pulsating jet engines: to study the theory of combustion, effect of turbulence on flame propagation and cooling, and to verify and augment existing theories by means of experimental investigation of ignition, combustion, flame holding, flame propagation and cooling.

Summary

The magnet for the moving-spark device, to be used in conjunction with the pyrex combustion chamber, has been received. An electrode arrangement for this device has been built and is now ready for tests.

An electronic flame-speed recorder has been built and preliminary tests have been carried out. The circuit has been modified to enable the measurement of a wider range of time intervals. Further slight modifications might be necessary in order to improve the sensitivity of the device.

The study of Bunsen burner flames disturbed by electrical fields and by sound waves has been continued. Application of the shadow technique to this work has enabled a comparison of the phenomena produced by sound disturbance in a flame and in the unlit gas jet. It has also led to a tentative explanation of the electrical flame-holding effect discovered in the course of this work.

An analysis was made of possible means to increase the mass flow in the air supply now available for burner experiments at Cornell Aeronautical Laboratory.

In the study of the possible catalytic influence of combustion chamber wall material, three types of refractory tubes have been tested in the ½" burner installation. The data in all cases were similar to those obtained on the metal tubes, with the exception that the temperature drop beyond the point of maximum temperature was less sharp.

The construction of a low-pressure mantled burner to be used for the investigation of combustion conditions on the emission spectra of hydrocarbon flames and of its attendant instrumentation is in progress. All the necessary equipment, parts, and materials now needed in this study are on order and work on the burner assembly is progressing as rapidly as the essential components arrive.

Progress

After delivery of the magnet for the moving-spark arrangement, tests were performed to determine the flux density as a function of distance along the axis of the magnet. The variations encountered have been rather large and may have to be compensated for if a constant spark velocity is to be achieved. An electrode arrangement, consisting of a brass bar as the lower electrode and a stretched wire as upper electrode, has been built and tests of the device have been started.

Tests of a trial circuit for the electronic timing device for flame-propagation measurement have been successful, and a unit was built which is capable of recording nine consecutive time intervals. The circuit utilizes ten thyratron tubes which can be fired by impulses received from ionization gaps or by any other devices for detecting the passage of the flame front at a certain point. In the original circuit, each time a thyratron fired, the single-sweep circuit of an oscillograph (Dumont Type 247) was triggered and at the same time the trace was displaced vertically by a small amount, so that a photographic record of a run consisted of nine parallel traces. The lengths of these indicated the elapsed time intervals. Accurate reading of the time was achieved by modulating the beam intensity with a known frequency.

In order to enable a wider range of time intervals to be measured and also to eliminate certain undesirable features inherent in the operation of the trigger circuit of the oscillograph, the circuit was subsequently modified to trigger the single sweep only once when the first thyratron fires. Thereafter, by means of an auxiliary recurrent vertical sweep, the cathode-ray traces out a two-dimensional pattern similar to a television scan. The pulses from the thyratrons are recorded as bright spots on this pattern by modulating the beam intensity, which is also modulated, as in the original circuit, with a known frequency for accurate time measurement. Tests so far performed have indicated that the device is capable of measuring, within a total time interval of 10 milliseconds, nine intervals to the nearest .05 millisecond. Of course, the horizontal and vertical sweep velocities can be adjusted at will in order to adapt the total time interval to the requirements of the particular experiment.

Since the sensitivity of the individual thyratron circuits varies somewhat owing to slight differences in tube characteristics and circuit parameters a modification of the circuits, allowing adjustment of sensitivity for each circuit separately, is contemplated.

A technical report on *Phenomena in electrically and acoustically disturbed Bunsen burner flames* has been issued, covering the work performed on this subject through August. The conclusion has been reached that the method of disturbed burner flames is of value for the study of hydrodynamical phenomena in distorted flame fronts and may lead to a better understanding of flame propagation under turbulent conditions.

The method and the experimental arrangement have been described in the last *Quarterly Report*. Examples of stroboscopic photographs of electrically and acoustically disturbed flames are shown, respectively, in Figs. 3 and 4. Area measurements

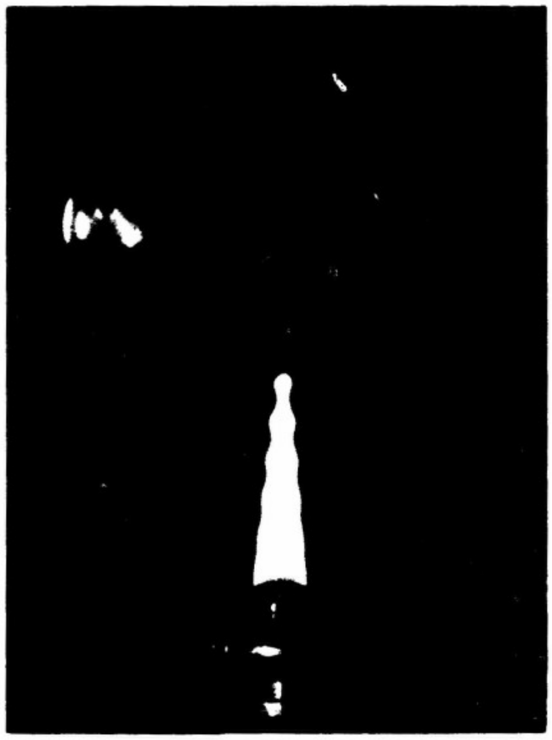


Fig. 3. Stroboscopic photograph of electrically disturbed flame. (Frequency 500 cycles per second.)

of distorted flame surfaces have been carried out and have confirmed the theoretical prediction that for constant-mixture composition the burning velocity is independent of amplitude, phase and frequency of the disturbance.

The generation of the distortion of the flame front by the disturbance appears to be due to an instability of the emerging gas jet immediately above the nozzle tip. Application of the shadowgraph technique permitted a comparison of the phenomena produced in the flame and in the unlit gas jet by the same acoustical disturbance. This comparison is as shown in Figs. 5 and 6. It is believed that instabilities of this nature play an important role in the operation of flame-holding devices. Preliminary experiments on flames burning on a rod-shaped flame-holder in the free gas

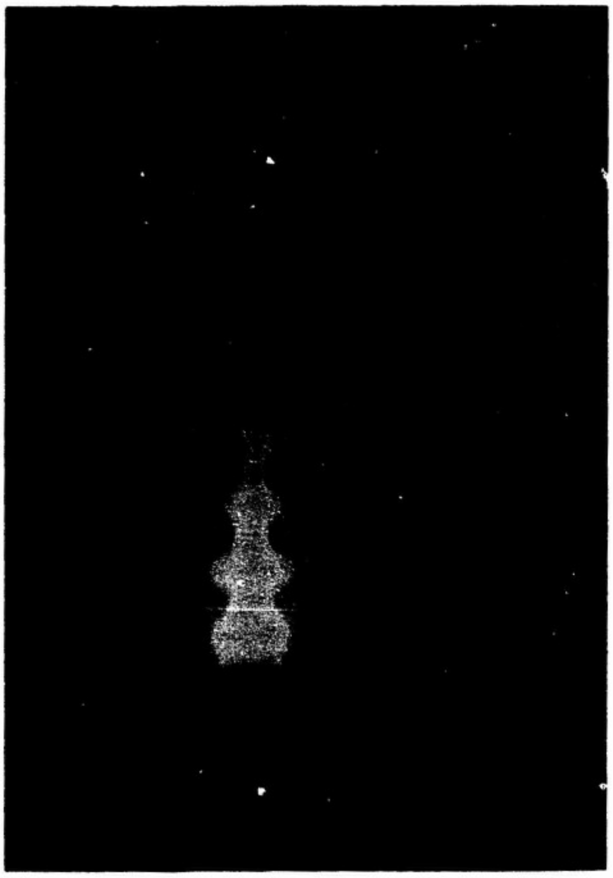


Fig. 4. Stroboscopic photograph of acoustically disturbed flame. (Frequency 200 cycles per second.)

jet have indicated that the degree of instability is larger in this case, since these flames tend always to vibrate spontaneously.

Fig. 3 shows that the distortion of the flame front increases in amplitude while travelling up along the cone. This phenomenon, always present for moderate intensities of the disturbance, indicates the appearance of a flow disturbance at the flame front, and is in qualitative agreement with theoretical predictions of a hydrodynamical instability of flame fronts by Landau.[1] While existing theories on flame propagation under turbulent conditions take into account only a passive distortion of the flame front by the turbulent motion in the unburnt gas, it would seem that the added creation of flow disturbances at the distorted flame front is fundamentally important and would have to be incorporated in any valid theory. Direct visualization and measurement of the flow pattern in disturbed flames by means of intermittently illuminated particles is now being attempted.

Application of the shadowgraph technique has led to a tentative explanation of the increase in blow-off limit under the influence of electric fields, which has been discovered in the course of this work. Figs. 7 and 8 show how the shape of the hot gas zone surrounding the flame is altered when a d-c field is applied to the flame. This change is presumably caused by the ion wind created by the field. It is believed that the hot gas pulled down at the nozzle tip precludes the entrainment of air, supplies the flame with chain carriers and raises the temperature at the nozzle exit, thereby increasing the local burning velocity and thus the blow-off limit.

A preliminary analytical investigation of the mixing process involved in an induction-type combustion channel has been completed and a report prepared. The investigation covered three possible conditions of mixing:

(1) constant-area mixing with inducing jet at $M = 1$ at the point of injection,

(2) constant-area mixing with uniform pressure across the section where mixing begins,

(3) constant-pressure mixing.

The investigation indicates the following:

1. Constant-area mixing is superior to constant-pressure mixing.

Fig. 5. Stroboscopic shadowgraph of acoustically disturbed flame.

[1] L. Landau, *Acta Physicochim.* URSS 19, 77 (1944).

Fig. 6. Acoustically disturbed gas jet corresponding to flame in Fig. 5.

2. Pumping efficiency increases as the induced air-stream Mach number at the beginning of mixing increases; but there is the obvious limitation that in the condition of minimum mixing losses, i.e. when the velocities of the two streams are equal, the pumping effect is reduced to zero.
3. An open-circuit, induction-type, $M = 2$, 21″-diameter wind tunnel could be operated continuously with the power plant now available in the burner laboratory of Cornell Aeronautical Laboratory.

A modified two-stage mechanical supercharger, taken from an Allison V-3420 engine and driven by an Allison V-1710 engine, was tested to measure the air mass flows obtainable with various delivery pressures. The preliminary tests indicate that between 10 and 11 pounds/sec. of air can be obtained at a pressure of 30 p.s.i. and at 3000 engine crankshaft r.p.m., with the supercharger's two stages operating in series.

In the investigation of the possible catalytic influence of combustion chamber wall material, tests were made using a fused quartz combustion tube with an internal diameter of ½″; data were obtained which were similar to those obtained with Inconel tube, except that when the quartz tube was insulated the slope of the curve downstream of the point of maximum temperature was less.

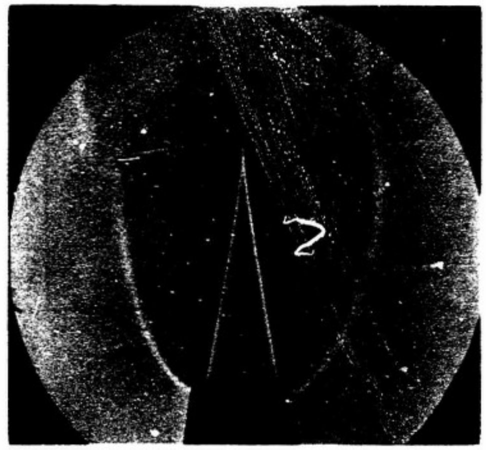


Fig. 7. Shadowgraph of undisturbed flame.

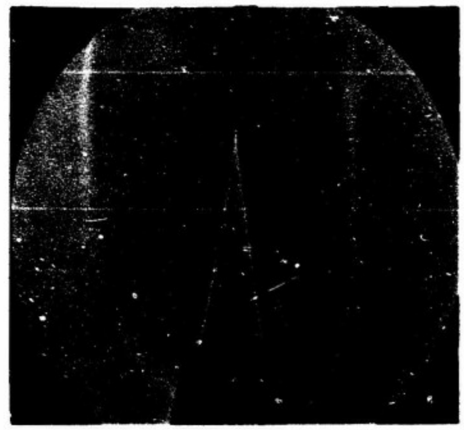


Fig. 8. Shadowgraph of flame subjected to a d-c field (nozzle is negative).

An aluminum silicate and a silicon carbide tube gave similar results; but since both of these tubes had extremely thick walls, it was necessary to increase the time at each flow rate in order that thermal equilibrium might be established.

Gas analyses are in progress on combustion gases taken at various points in the burner.

All the data recorded to date are presently being reduced and analyzed. On the basis of these analyses, definite conclusions will be reached on the catalytic activity of each of the materials used.

The application of spectrography to the study of reaction mechanisms, particularly by infrared spectrography, has been started.

A sketch of the burner and the gas metering equipment used in this investigation is shown in Fig. 9. Methane from a cylinder is reduced to a low pressure through a two-stage reducing valve,

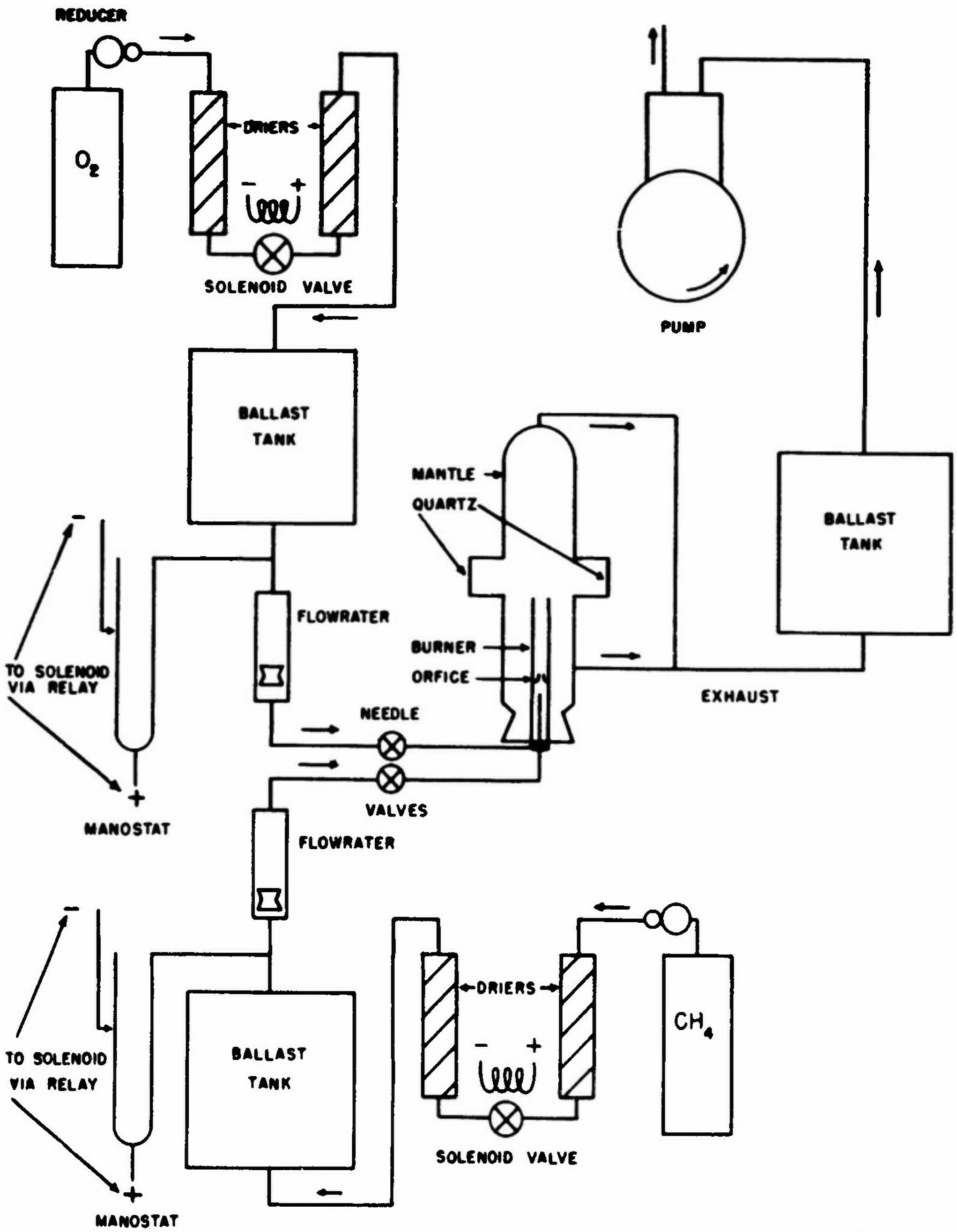


Fig. 9. Low pressure burner assembly.

passed through a drying tube, a flow-controlling solenoid valve, a second drying tube, and into a ballast tank. From the ballast tank, the gas is metered through a flow-rater and a needle valve into the burner. Oxygen is metered into the burner through a similar system. The two gases are mixed as they pass through a small orifice situated below the lip of the burner. A manometer, fitted with electrical contacts, is connected to each ballast tank in each feed-line and controls the supply of gas by activating the solenoid operated valve. The pressure in the feed-system is maintained slightly higher than the burner pressure. The combustion products are removed from the burner and a low pressure is maintained therein by a high capacity vacuum pump which evacuates the system through a third large ballast tank.

The flame is ignited by a spark between tungsten electrodes sealed through the burner-mantle just above the lip of the burner.

The flame is observed through quartz windows sealed to the side-arms of the burner-mantle. The operation of the burner is automatic once the pressure controls have been set.

The spectrographic data will be recorded with a B & L Littrow Model Quartz Spectrograph and a Perkin-Elmer Infrared Spectrograph. The burner assembly is unitized and portable so that it can be set up in conjunction with either instrument.

Plans

After completion of preliminary tests of the moving-spark device, the pyrex combustion chamber will be redesigned to fit the magnet, and actual combustion experiments will be started.

Flame propagation experiments in a long pipe, utilizing the electronic timing device, are planned as soon as tests of this device have been concluded.

Work on burner flames will be continued. A systematic evaluation of the influence of amplitude and frequency of the disturbances applied to the flames is planned. Investigation of flames lifted from the burner, either held by a flameholder or burning freely in the gas stream, will be continued. Flow visualization by means of illuminated powder techniques, and application of shadow and striae methods to this work, will be investigated.

In connection with the investigation of the possible catalytic influence of combustion chamber wall material on the efficiency and overall capacity of the chamber, the next step will be the reduction and analysis of the data which has already been obtained in this study. To facilitate this part of the work and to assist in the formulation of detailed future plans, the services of a consultant have been retained.

If no catalytic activity is indicated by the data, a recommendation to drop this investigation will be in order. However, if the results are positive and catalytic effects are found, then further experiments to evaluate these effects will be in order. In either event, a study will be made to determine the exact influence of the comparative heat transfer coefficients of the various materials on the empirical method which has been used to date.

In connection with the spectrographic studies of combustion, the immediate task is the completion of our low-pressure burner and its assembly, the assembling and checking of our infrared spectrograph, and the recording of preliminary spectrograms. It is anticipated that examination of the flame in the ultraviolet region will also be profitable.

PHASE NO. 3

In connection with pulsating jet engines: to undertake experimental investigation of temperature- and fatigue-resistant materials for intake valves and coatings, and of fabrication methods and techniques to cover said materials.

Summary

Evaluation of sheet stock alloys for high temperature pulse jet applications is being made on the basis of high temperature vibrating fatigue, tensile, and creep properties. Future consideration will be given to tensile fatigue and repeated shock tests. Concurrent with the collection of such design data, attempts are being made to interpret the results and to picture more clearly the nature of high temperature failure.

In all three of the above test assemblies, instrumentation has been carried to the point where routine testing is underway. AF-18 stainless steel and regular Inconel sheet stock are under present investigation in the temperature range of 1200° to 1800°F alloy.

Progress

In the course of investigating the suitability of available high temperature sheet stock alloys for pulse jet applications, consideration is being given to the following pertinent high temperature properties:

1. vibrating fatigue,
2. tensile properties,
3. creep,
4. tensile fatigue,
5. repeated shock or impact.

While the high temperature fatigue characteristics no doubt will be the controlling factor in the selection of alloys for intake valve parts, the remaining properties listed above should supply supporting data useful for design purposes. At present, testing facilities have been completed for examining the first three properties.

In addition to the mere accumulation of mechanical property data, it would be desirable to attempt correlation of the above properties in an effort to further our understanding of high temperature failure and thereby provide sound basis for the development of better high temperature materials. A tool which may aid in this latter effort is the high temperature metalloscope currently under SQUID development.

The following are the sheet stock alloys which are under study or in the process of being prepared for testing: Type 310 + 2 silicon stainless steel (AF-18), regular Inconel, S-816. Additional available materials will be considered as the program progresses.

High Temperature Fatigue Test. Although all the auxiliary instrumentation is not available

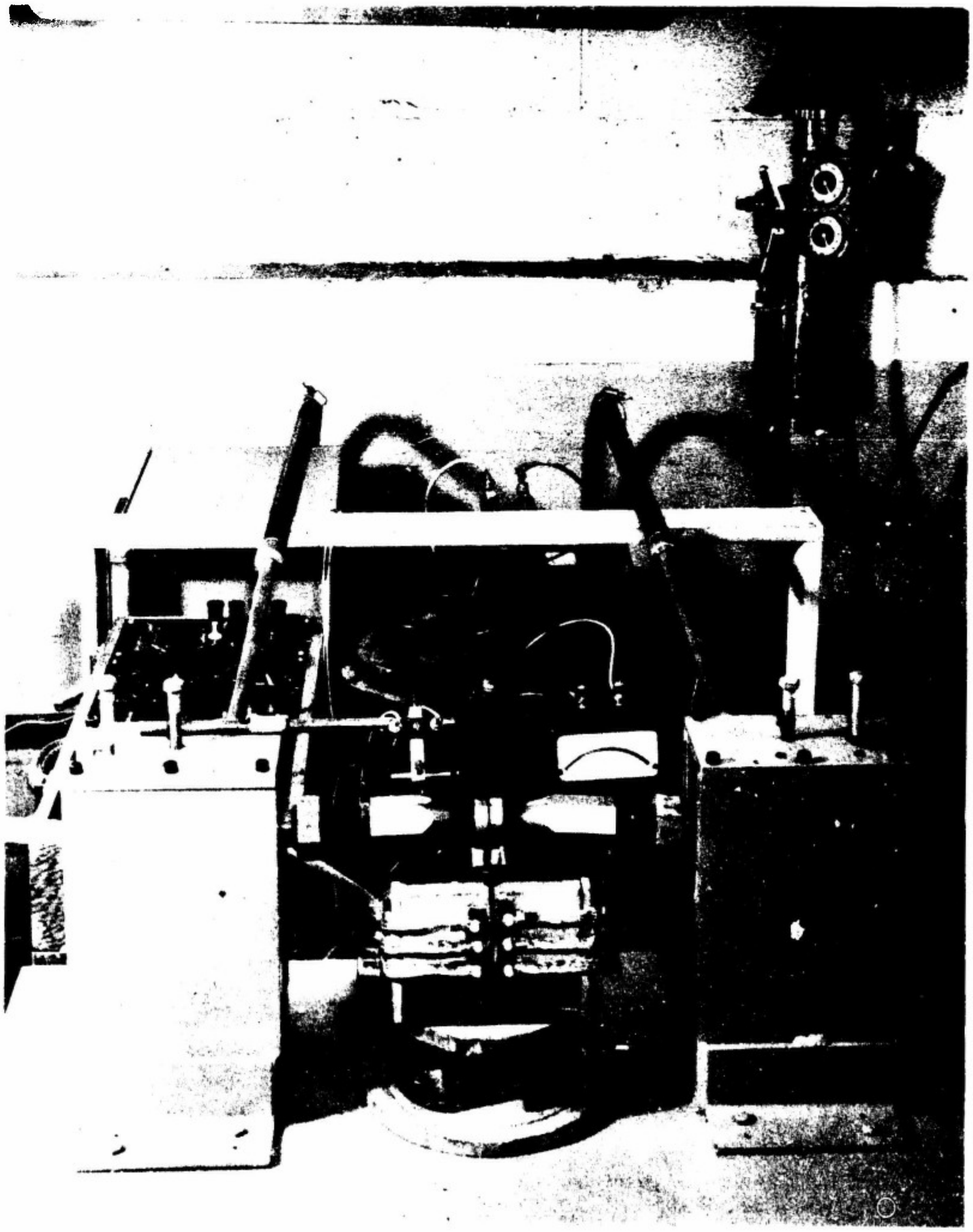


Fig. 10. High temperature pneumatic fatigue machine for sheet stock.

as yet, the pneumatic fatigue machine has been assembled into a usable unit. As a temporary substitute for the micromax temperature controller, a variable transformer is being used to control the test temperature manually. Deflection measurements are being made with a steel scale graduated in 1/64" until the micrometer slide device is available. The present arrangement of equipment is shown in Fig. 10.

The original Globar furnace that was built as a specimen heat source did not prove satisfactory because of the temperature gradient over the critical section of the specimen and because of insufficient control of temperature. It was redesigned to accommodate six Globars instead of two, and this arrangement has proved to be quite satisfactory.

A series of tests were run to determine the best method of measuring the temperature at the critical section. Results showed that a thermocouple tied to the specimen with asbestos string gave good correlation with one welded to the specimen. A very light gauge (No. 28) chromel-alumel couple is used so that no restraint is imparted to the resonant vibrating specimen.

Tests have been made on AF-18 and a curve determined for 1400°F. A series of tests at 1600°F is now in progress. Runs will also be made at 1800°F and, if an alloy shows promise, at 2000°F. Once the curves have been established, the deflection measurements will be evaluated in terms of strain so that the data will be more useful for design purposes. This will be attempted by means of high temperature strain gauges. Inasmuch as some of the test deflections used exceed the elastic limit, it is felt that a plot of strain versus number of cycles will be more useful than stress versus number of cycles both from a practical design standpoint and as a means of comparing different alloys.

High Temperature Tensile Tests. A high temperature tensile testing program has been initiated, not only to obtain values of tensile properties at high temperature which can be used for design data, but also to acquire some information as to the method by which metals deform and fail at elevated temperatures. Tensile tests have been conducted on AF-18 stainless steel sheet at 1200, 1500, and 1800°F using several different strain rates at each temperature. The strain rate was held constant during the course of each test with the help of a time-strain recorder system developed for this purpose.

The results of these tests show that at 1200°F the rate of straining has no effect on the values of tensile and yield strengths, while at the higher temperatures increased strain rates result in higher tensile and yield strengths. The effect of strain rate is related to two processes which occur in specimens tested at the higher temperatures—strain hardening and recrystallization. Recrystallization occurs above a certain temperature (somewhere between 1200° and 1500°F in AF-18) and softens the metal which is hardened by straining. Consequently specimens tested at 1200°F experience no softening and harden to the same ultimate strength regardless of rate of straining. At higher temperatures, however, the strength depends on how much time is available for recrystallization to occur during the course of the

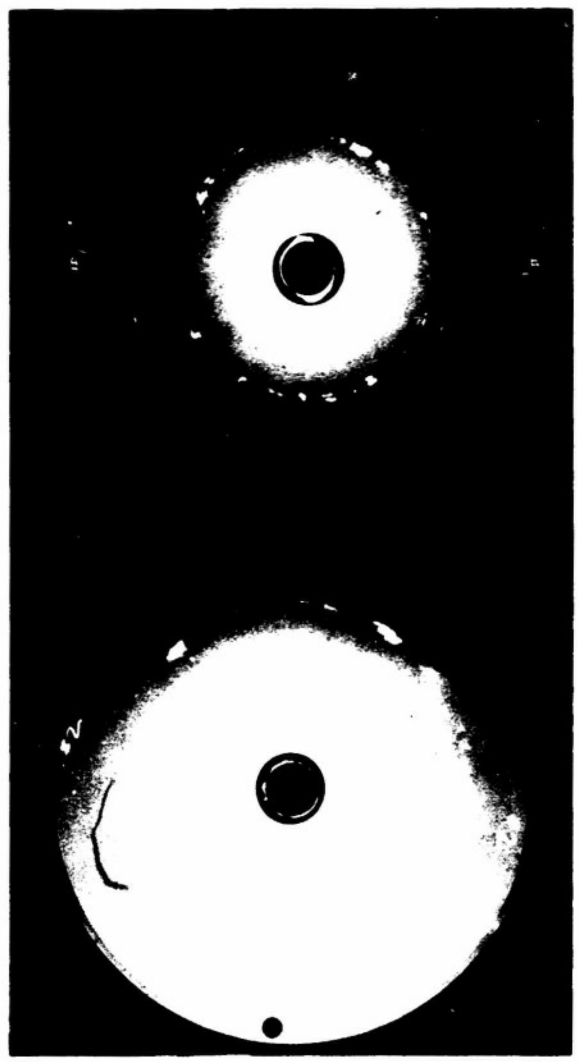


Fig. 11. Radiograms of AF-18. Elongated 1% at 1200°F.

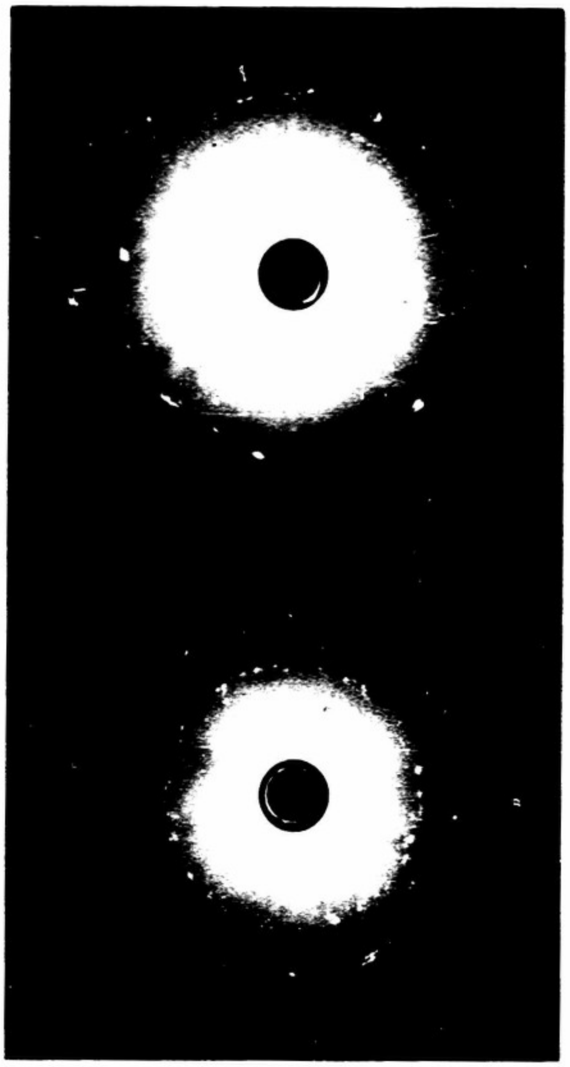


Fig. 12. Radiograms of AF-18. Elongated 1% at 1800°F.

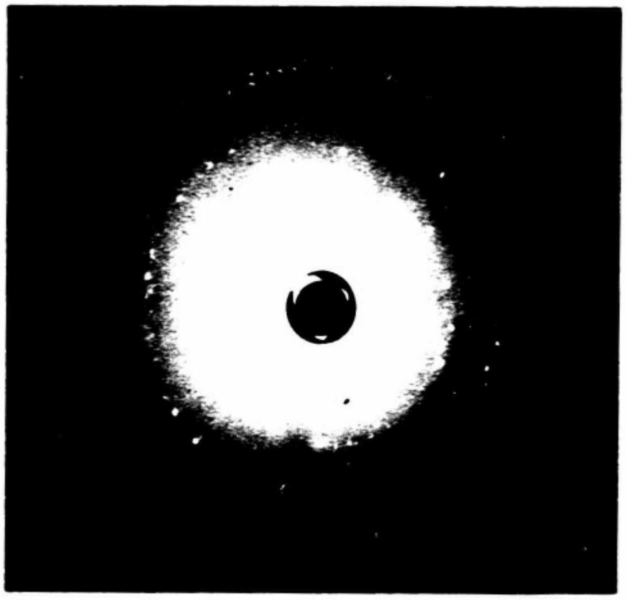


Fig. 13. Radiogram of AF-18. Annealed at 2000°F.

test, and consequently strain rate is an important variable in controlling the strength characteristics at the higher temperatures.

Several X-ray diffraction pictures were made to correlate these variables of strain rate, temperature, and recrystallization. Four specimens were strained to 1% elongation, two at high rates of strain at 1200° and 1800°F and two at slow rates of strain at the same temperatures. X-ray diffraction photographs of these specimens are shown in Figs. 11 and 12, and one of the original material in Fig. 13. The original material consisted of large strain-free grains as evidenced by the sharp spots. The two samples tested at 1200°F show signs of cold work or strain hardening, indicated by broadening of the spots into short arcs, as does the sample strained rapidly at 1800°F. The specimen slowly strained at 1800°F, however, consisted mainly of newly formed strain-free grains which appear as fine sharp spots. A similar program of tensile testing is being conducted on regular Inconel sheet material to obtain tensile data and to determine the temperature below which strength is independent of strain rate.

High Temperature Strain Gauge. The high temperature strain gauge for sheet stock developed previously under the Bumblebee program[2] has been improved both in durability and convenience of operation. Two of the improved gauges have been built and one is illustrated in Fig. 14.

High Temperature Creep Tests. Instrumentation of a creep testing unit has been completed and tests on AF-18 have been initiated. It is felt that such data should be of value in determining the load carrying ability of materials at least at the higher temperatures where the tensile tests have indicated a strain rate effect on strength properties.

High Temperature Metalloscope. With the arrival of the Tocco Heat Gun and the Pyrex glass furnace chamber, it has been possible to make progress in the construction of this equip-

[2] Termination Report on Combustion Chamber Design Improvements, CAL Report No. CF-710, June 30, 1947.

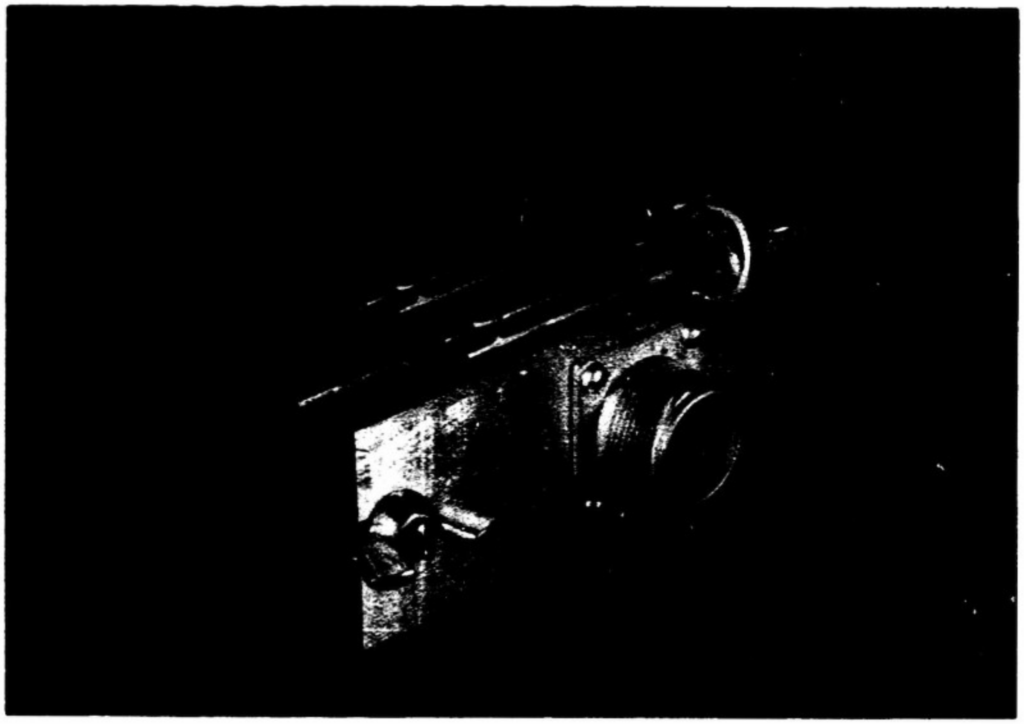


Fig. 14. High temperature strain gauge.

ment. As soon as the induction equipment was checked out as satisfactory, experiments were conducted to determine its degree of efficiency as a heat source. The specimens were found to heat up inside the glass chamber very well. An interesting reaction was encountered when small specimens were heated. If the specimen was not centered in the flux pattern it was tossed several feet into the air by the magnetic forces. A study of the flux pattern showed it to be somewhat umbrella shaped, and placing the specimen at the top of the umbrella reduced this difficulty. Gross movements of the specimen will be eliminated in practice by cementing the specimen to the stage with ceramic cement, but a very small vibration may be set up which will hinder microscopic work. This will be unknown until the optical system, which has been partly received, is assembled. Fig. 15 shows the Heat Gun mounted on a pedestal with leveling screws and the cage which is arranged so it can be used to raise and lower the furnace from the end of the Gun. When the heating experiments are completed, a series of vacuum experiments will be started using a megavac forepressure pump which has been received. Shipment of the diffusion pump is promised for 27 November.

Plans

Activity in this program during the coming three months will be concerned primarily with the accumulation of data on materials at high temperatures, which can be applied directly to the design of pulse jet valve mechanisms. While refinements in equipment and technique are still being made, it is now possible to go ahead with the high temperature fatigue, creep, and tensile testing program for sheet stock alloys.

Vibrating Fatigue Tests. The object of these tests is to establish stress or strain versus cycles-to-failure diagrams, in order to indicate directly the expected life for an alloy at the specified operating temperature. With tests being conducted at temperatures of 1200, 1400, 1600, and 1800°F, it is expected that such information will be obtained for two materials; namely, AF-18 stainless steel (25-20 + 2 silicon) and regular Inconel during this period. Attempts will be made to measure the actual strains in the test specimen and use this variable rather than specimen deflection for correlation with fatigue life.

High Temperature Tensile Tests. High temperature tensile tests at various strain rates will be continued and data should be obtained in the 1200 to 1800°F temperature range for regular In-

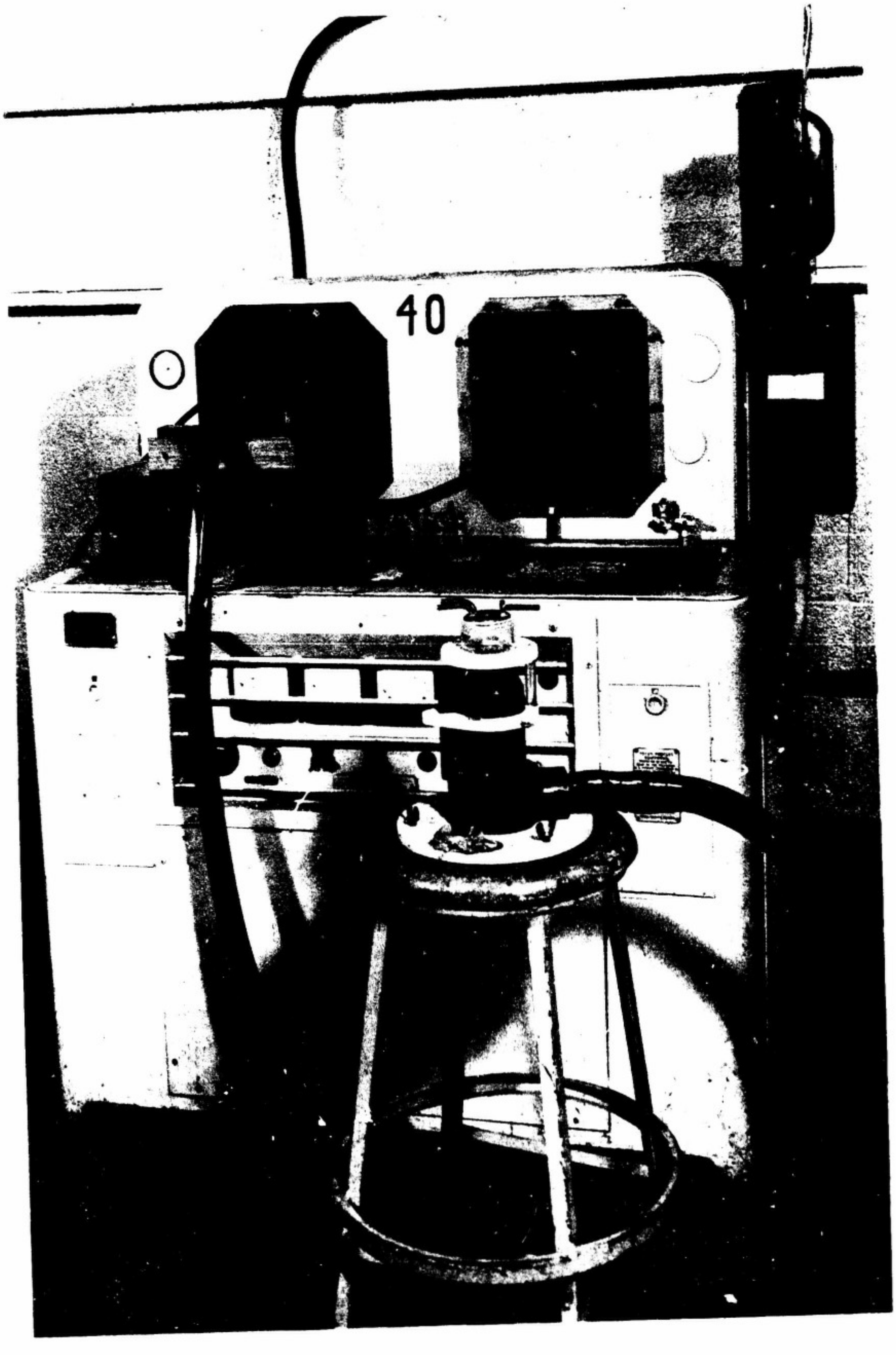


Fig. 15. Induction heat source for high temperature metalloscope.

conel and S-816 material similar to that which has been reported for AF-18. This type of data is proving of interest not only from the standpoint of classifying the different materials according to high temperature strength but also by indicating to some extent the nature of high temperature deformation and failure.

High Temperature Creep Tests. Short-time creep testing has begun on sheet stock material to identify limiting stresses for specified deformations in the temperature range of 1200 to 1800°F. Evaluations of this type will be completed for AF-18, regular Inconel, and preliminary determinations for S-816 will be under way.

High Temperature Metalloscope. Progress in this activity is being controlled for the most part by delivery of component parts of the apparatus. No delivery date is available for the optics. Necessary apparatus for the vacuum system is promised for delivery on 27 November 1947; construction of this part of the metalloscope will then be initiated. The feasability of using the Tocco Heat Gun as a heating source will be established; and if promising, a temperature control system will be devised.

Concluding Remarks. Progress in this project has reached the level where actual data for evaluating the suitability of alloys for high temperature service is underway. During the next three months classification of AF-18 stainless steel and Regular Inconel will be made from the standpoint of fatigue, tensile, and creep characteristics. In addition correlation of these properties with each other and the several materials will be attempted.

This pattern of activity will get under way a means for specifying materials for pulse jet applications and provide a way of thinking about the mechanism of high temperature failure.

QUARTERLY PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH

ON LIQUID ROCKET AND PULSE JET PROPULSION

FOR THE

BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

CONTRACT N6ORI-105, TASK ORDER III

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY
1 OCTOBER 1947

In connection with liquid rockets and pulsating jet engines; to investigate theoretically and experimentally (1) the stability of laminar boundary layer, (2) the interaction of boundary layer with external flow field at supersonic velocities as it affects pressure distribution around bodies of revolution, airfoils, etc., and (3) the interaction of shock waves in channels and diffusers.

Progress

EQUIPMENT. The task of overhauling and cleaning the two Worthington compressors is completed. A Worthington representative will return for a final check-up before the compressors are run. The transformers are installed and the electrical wiring from the secondary to the motors completed. A fence is being erected around the transformer pit and the primary will shortly be connected. A ten horsepower line is being installed to supply power for the air compressor that will furnish air for the pressure control system of the pilot tunnel.

The air bottles are in place and bolted to the concrete foundations. Installation of the piping for the air supply system is scheduled to begin sometime in the next few weeks.

Detailed design of the wind tunnel proper was finished and blueprints were submitted to several contractors. A sufficient number of estimates have been received and the contract will be awarded to a nearby machine shop in the next few days. The delivery time estimated by the contractor is sixty days from the time of receipt of all the material which we will supply from Navy stock.

The overhead crane system for the test room is ordered and should be installed this month. The work of soundproofing the test room walls, installing lighting fixtures, etc., will then be resumed.

OPTICAL APPARATUS AND INSTRUMENTATION. The Naval Gun Factory has nearly completed the fabrication of the 4" interferometer plates, and our instrument shop has made good progress on the fabrication of the mounts. A general assembly drawing of the interferometer carriage and lifting jack has been completed and estimates of the cost of construction will soon be obtained.

After a study of the optical and mechanical problems involved in supporting airfoil models by means of slots cut in the glass windows, it was decided to use relatively inexpensive Schlieren-quality plate glass windows for the initial tests. A final decision on the method of airfoil support for the interferometer-quality 9" windows will be deferred until after these tests have been made. Meanwhile the 4" interferometer can be used for fundamental boundary layer and shock interaction studies in the pilot tunnel and with the 4" windows in the large tunnel.

The Schlieren mirrors have been received and mounts for the 4" mirrors were fabricated in our instrument shop.

All pressure gauges and the temperature recorder have been received. A dew-point meter will shortly be ordered. Samples of the air obtained from the settling chamber during the course of a run will be stored in small air flasks and later analyzed with the dew-point meter. This technique will be investigated first in the pilot tunnel.

PILOT TUNNEL. Concrete slabs for the two air bottles and the compressors are in place and this equipment installed. The piping and settling chambers are fabricated, but delivery is temporarily delayed by an Express strike in New York in which the pressure control system is caught. The supporting framework for the settling chamber is nearly completed.

The test channel has arrived and the $M = 3.0$ nozzle blocks are being cast in a nearby foundry; they will be machined in our shop.

THEORETICAL STUDIES. (a) A theoretical analysis has been completed of the phenomena that occur when heat is suddenly added to a section of a straight tube in which a gas is flowing with uniform velocity. One of the aims of the investigation was to study the mechanism by which a new steady flow is established when sufficient heat is added to "choke" the original flow. The results are contained in a *Technical Report* now in preparation.

(b) Based on the investigation in (a), which involved the generation of compression and expansion waves by the sudden input of heat, a study is now in progress of a new type of valveless aeroresonator which is mechanically simple and possibly more efficient than either the pulse jet or the ram jet. Calculations are in progress of the cycle in the valveless aeroresonator with the assumption of instantaneous, constant-volume burning. This simplified model was chosen in order to give some insight into the gas dynamic aspects of such an engine.

(c) A *Technical Report* on the theoretical aspects of boundary layer-shock wave interactions in supersonic flow will be submitted by 1 November, 1947.

Future Plans

During the next few months, the main efforts of the personnel engaged in Phase 1 will be directed along the following lines:

1. completion of the high-pressure air supply system and the supersonic blow-down tunnels and execution of initial calibration runs,
2. an integrated program of theoretical and experimental studies with the aid of the "pilot" blowdown tunnel which will be in operation in November.

A. Condensation of Components of Air at High Mach Numbers. Theoretical calculations of the condensation point of supersaturated nitrogen and supersaturated oxygen in air have been completed. Tests which are planned for the pilot tunnel will furnish an experimental check on the theoretical work. These tests will indicate the extent of pre-heating necessary to avoid condensation, and also the maximum Mach number that can be reached without preheating.

B. Boundary Layer—Shock Wave Interaction. Some progress has been made in a theoretical study of fundamental interactions such as the reflection of an incident oblique shock at a plane wall. To check the theoretical conclusions already reached and to guide the theoretical work, an experimental study will be carried out in the pilot tunnel on this and similar problems over a wide range of Reynolds numbers and shock strengths.

C. Triple-shock Interaction. Experimental work will also be carried out on the triple or Mach-shock intersection between the oblique shocks from two wedges mounted in a supersonic channel. The chief aim is to determine the effect of viscous forces (if any) on this interaction in an attempt to clarify the existing discrepancies between theory and experiment.

Other Theoretical and Experimental Studies. (a) *Stability of the Laminar Boundary Layer.* Our previous work on the stability of the supersonic laminar boundary layer will be extended to the case with pressure gradient. The results of this work, if successful, will be applied to determine the character of the boundary layer over the airfoils to be tested in the large supersonic tunnel.

(b) *Valveless Aeroresonator.* Theoretical calculations of the cycle in the valveless aeroresonator will be continued. Experimental studies are also planned, but these studies will not be connected with Phase 1.

PHASE NO. 2

To study (1) the characteristics of combustion in high-velocity fuel-oxidant streams, ignitibility, efficiency, after-burning, thrust, etc., (2) effects of sub-atmospheric pressures, (3) interactions between ionization and flame, (4) observation of optical and mass spectra, and (5) theory of adiabatic exothermic reaction.

This phase is jointly sponsored with U. S. Bureau of Ordnance APL-JHU associated contract number NOrd-7920, Task PRN-3.

Progress

In connection with interpretation of burning velocity measurements, calculations of equilibrium atom and radical concentrations have been made for mixtures of ethane, ethylene, or acetylene with oxygen. Flame speeds increase in the above order. This is ascribable to increased atom and radical concentrations resulting from increasing flame temperatures.

Some progress has been made in the study of diborane. Mixtures with oxygen appear not to ignite spontaneously at room temperature, in contrast to the behavior of aluminium borohydride and boron triethyl.

It has been confirmed that hydrogen atoms from a discharge tube induce the formation of hydrogen peroxide from hydrogen and oxygen providing the off-gases are immediately condensed at liquid nitrogen temperatures.

The special type of mass spectrograph which has been developed as a leak detector utilizing helium has proved inapplicable to heavier particles, although it will pick up hydrogen atoms.

PHASE NO. 3

To investigate theoretically and experimentally certain basic problems associated with the development of propulsive devices of the ducted type. Specifically these problems are:

1. Mixing of primary and secondary streams,
2. Study of schemes to improve mixing,
3. Combustion chamber problems of ducted rockets.

Summary

I. A theoretical investigation of the injector half of a ducted rocket propulsion system is in process. Quantitative results are currently being computed.

II. A two-dimensional mixing channel incorporting supersonic jets of various Mach numbers, 1½″ deep with ¼″ throats, has passed the preliminary design stage and the detail design is proceeding.

III. Preliminary studies of the complete ducted rocket system for use in the later stages of this program are being carried out.

Progress

I. Theoretical Studies. A preliminary theoretical investigation of the induction of air into a tube by the action of the exhaust of a rocket has been begun. This study is intended to give a rough idea of the performance to be expected from such a unit.

The approach being used initially for the general study is similar to that employed in ejector studies but involves parameters which apply directly to a rocket used as the primary jet. One-dimensional compressible gas flow theory is used assuming a supersonic rocket exhaust at free stream static pressure. The pressure of the induced air is not necessarily assumed equal to the free stream value, since the rocket exhaust is supersonic.

The mechanism of the mixing process is not considered; the rocket exhaust and the induced air are assumed to be completely mixed at some station down the tube. This simplified analysis has been completed and quantitative data are being computed.

Qualitatively the flow solution indicates an analogy between this type of flow and the flow of air in a tube with heat addition.

The results of this analysis will be compared with the actual flow obtained in the two-dimensional channel when completed, and the assumptions made therein will be examined critically in order to develop a more accurate theory of the process.

Experimental Equipment. A two-dimensional mixing channel has been designed in which a small supersonic stream is used as an injector to induce air through a variable channel. The process of the mixing of subsonic air with one of several supersonic flows can be observed and photographed.

The supersonic jets of four Mach numbers (1.5, 2.0, 2.5 and 3.0) will be two-dimensional in form and will be contained between two transparent walls 1½″ apart. The throat will be ¼″ in each case. These jets will be driven by the air supply used for the supersonic pilot tunnel of Phase 1. Running times of the order of four minutes at constant pressure will be available.

The entire channel will be 42″ wide by 1½″ deep and about eight feet long. The walls of this channel will be transparent to allow photographic observation of the flow. The air jet will exhaust down the center, inducing a secondary flow in the rest of the channel. Air for this purpose is drawn from the outside and the products of mixing are also exhausted outdoors. The width and contour of the channel may be varied over wide limits.

Flow observations will be made using the Schlieren and Shadowgraph methods. The secondary flow will be studied by means of temperature and pressure traverses. In addition the quantity of induced air will be measured.

It is expected that this equipment will be assembled for preliminary tests in the month of December.